Carbon Sequestration Leadership Forum
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TECHNICAL GROUP

Update of
CSLF Technology Roadmap

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UPDATE OF CSLF TECHNOLOGY ROADMAP

Note by the Secretariat

Background

At the October 2009 meeting of the Technical Group in London, there was consensus that the Technical Group should proceed with an update to the CSLF Technology Roadmap, as the Roadmap is a "living document" that needs revision to keep up with advances in carbon capture and storage (CCS) technologies. At the March 2010 meeting of the Technical Group in Pau, a schedule was developed for completing the new draft of the Roadmap, and with the assistance of CSLF Members and the Global CCS Institute, an initial draft of the updated Roadmap was completed at the end of July. In August this draft was reviewed first by the CSLF Projects Interaction and Review Team (PIRT) and then by the entire Technical Group. Comments received have been considered and incorporated into the current draft.

Action Requested

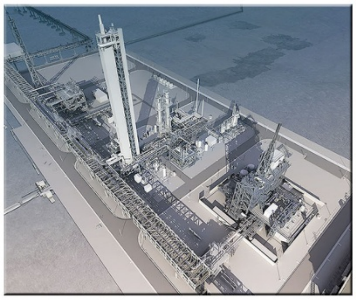
The Technical Group is requested to review and approve the updated CSLF Technology Roadmap.

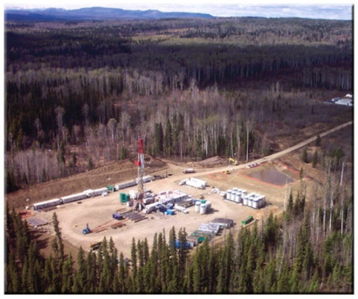
2010

Carbon Sequestration Leadership Forum Technology Roadmap

A Global Response to the Challenge of Climate Change

2010 CSLF Technology Roadmap





Cover Photo Descriptions:

Top to Bottom:

CO_2 Technology Centre Mongstad

Krechba CPF at In Salah, Algeria

Regional Partnerships SECARB Unit

Nicolas Aimard presents operational aspects of the Lacq Integrated CCS Project to the CSLF Technical Group

Left to Right:

Fort Nelson CCS Project site

ZeroGen Storage Infrastructure

Dr. Peter Cook addresses Otway Community Meeting

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MODULE 0: INTRODUCTION

0.1. Context

Carbon dioxide (CO_2) capture and storage (CCS) can play a critical role in tackling global climate change. In order for it to be an effective part of the solution, CCS must be demonstrated as soon as possible with wide deployment before the target date of CCS commercialization by 2020. A prerequisite to this achievement is the establishment of the technical foundation for affordable capture, transport, and safe and effective long-term geologic storage of CO_2 as quickly as possible.

This Technology Roadmap (TRM) has identified the current status of CCS technologies around the world, the increasing level of activity in the industry, the major technology needs and gaps, and the key milestones for a wide development of improved cost-effective technologies for the separation, capture, transport, and long-term storage of CO_2.

Implementation of national and international pilot and demonstration projects is seen as a critical component in the development of lower-cost, improved capture technologies and safe long-term storage. The demonstration projects have to be built in parallel with research and development (R&D) efforts in order to close the technological gaps as cost effective as possible.

The Carbon Sequestration Leadership Forum (CSLF) will continue to catalyze the deployment of CCS technologies by actively working with member countries, governments, industry, and all sectors of the international research community on the strategic priorities outlined in this TRM. The CSLF will also continue to work with existing and new support organizations, such as the Global Carbon Capture and Storage Institute, in order to efficiently utilize scarce world resources and effort and to ensure that key technology gaps are addressed and closed.

The first CSLF TRM was developed in 2004 to identify promising directions for research in CCS.

The TRM was updated in 2009 to take into account the significant CCS developments that have occurred during the 2004 to early 2009 period and identified key knowledge gaps and areas where further research should be undertaken. This document is an update of the 2009 TRM. The main changes from the 2009 TRM are:

- Stronger emphasis on CCS integration and demonstration;
- Differentiation between demonstration and R&D; and
- Expanded and more detailed milestones for capture.

Since the last CSLF TRM update, significant international activity in the CCS field has occurred. The International Energy Agency (IEA) issued a TRM in 2009 (IEA, 2009) that addressed not only the technological aspects of CCS but also financing, legal and regulatory issues, public engagement as well as education and international collaboration aspects. In early 2010, the European Technology Platform for Zero-Emission Fossil Fuel Power Plants (ZEP) issued recommendations for research to support the deployment of CCS in Europe beyond 2020 (ZEP 2010). This 2010 update of the CSLF TRM has benefitted from these two documents and supplements and expands on recent developments in technology.

Significant CSLF project activity has occurred in the period 2004–2009, and substantial progress has been made in all aspects of CCS, resulting in successful completion of the early milestones identified in the timeframe 2004–2010. For example, there are now 30 recognized CSLF projects demonstrating worldwide collaboration on CCS and contributing to the CCS knowledge base. Completed projects include:

- Alberta Enhanced Coalbed Methane Recovery Project
- CASTOR
- China Coalbed Methane Technology/CO_2 Sequestration Project
- CO_2 Capture Project (Phase 2)
- CO_2STORE
- Dynamis
- ENCAP
- Frio Project
- Regional Opportunities for CO_2 Capture and Storage in China

Projects under way include:

- CANMET Energy Technology Centre (CETC) R&D Oxyfuel Combustion for CO_2 Capture
- CCS Northern Netherlands
- CCS Rotterdam
- CO_2CRC Otway Project Phase II
- CO_2 GeoNet
- CO_2 Separation from Pressurized Gas Stream
- CO_2 SINK
- CO_2 Storage in Limburg Coal and Sandstone Layers
- Demonstration of an Oxyfuel Combustion System
- European CO_2 Technology Centre Mongstad
- Feasibility Study of Geologic Sequestration of CO_2 in Basalt Formations of (Deccan Trap) in India
- Fort Nelson Carbon Capture and Storage Project
- Geologic CO_2 Storage Assurance at In Salah, Algeria
- Gorgon LNG Project
- Heartland Area Redwater Project (HARP)
- IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project
- ITC CO_2 Capture with Chemical Solvents
- Lacq CO_2 Capture and Storage Project
- Regional Carbon Sequestration Partnerships
- TX Energy Carbon Management and Gasification Project
- Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project
- ZeroGen

At the time of this writing, several medium scale (10–50 MW) capture plants were being planned or launched as a result of extensive R&D, but there has not been sufficient experience upon which to draw operational conclusions. On the research side work has continued with existing absorption processes, solid adsorbents and membrane, and significant progress has been made at the laboratory scale. Some important learnings regarding capture technologies have been summarised in a forthcoming report from the IEA Greenhouse Gas R&D programme (IEA GHG, to be published). Although the summary is based on studies issued by IEA GHG in the peiod

2005–2009, the findings are universal. One finding is that for post combustion capture, solvent scrubbing is considered the state-of-the-art and that solid adsorbents and membranes based processes are considered to be second or even third generation technologies. The latter also holds for pre-combustion and oxyfuel. Further, efforts to improve the solvent scrubbing capture systems need to be continued as the main challenge is reduce the capture cost. The report also concludes that CO_2 capture has a net environmental benefit, due to the avoidance of CO_2 emissions. However, there is a valid concern regarding environmental effects related to solvent losses and other wastes produced from the capture plants. The same IEA GHG report indicates that it is of uttermost importance that governments provide financial support for storage resource exploration and for the development of the first commercial-scale CCS projects, to have robust CCS policies that provide certainty to investors and to support ongoing technical development.

An important achievement in CO_2 transport is the first off-shore CO_2 pipeline that was built in the Snøhvit Field in the Barents Sea off Northern Norway. This pipeline, which has been in operation for two years, is about 160 km long and transports 0.7 million tons per annum of CO_2.

The first commercial scale storage projects (Sleipner, In Salah, and Snøhvit) have shown that geological storage of CO_2 in saline aquifers is technologically feasible and they have added significant knowledge on monitoring and verification technologies, including use of remote sensing.

Regulatory frameworks will influence technical decisions. There is still some concern whether CO_2 is classified as a waste or not, and what types and quantities of impurities are acceptable in the stored CO_2, but the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter http://www.imo.org/Conventions/contents.asp?topic_id=258&doc_id=681 and the OSPAR Convention http://www.ospar.org/ have been amended to allow CCS.

Updates to this document will be made on a regular basis so that the TRM remains a living document and reference point for future carbon capture and storage technology development and deployment.

0.2. The Purpose of the CSLF TRM

This TRM is intended to provide a pathway toward the commercial deployment of integrated CO_2 capture, transport, and storage technologies. Specifically, the TRM focuses on how to:

- Through technologies and learning opportunities, achieve commercial viability and integration of CO_2 capture, transport, and storage;
- Develop an understanding of global storage potential, including matching CO_2 sources with potential storage sites and infrastructure needs;
- Address risk factors to increase confidence in the long-term effectiveness of CO_2 storage; and
- Build technical competence and confidence through sharing information and experience from demonstrations.

The TRM aims to provide guidance to the CSLF and its Members by:

- Describing possible routes to meet future integrated CO_2 capture, transport, and storage needs; and
- Indicating areas where the CSLF can make a difference and add value through international collaborative effort.

The TRM will also assist the CSLF in achieving its mission to facilitate the development and deployment of CCS technologies via collaborative efforts that address key technical, economic, and environmental obstacles. Information concerning the CSLF, its Charter, and its activities can be found at http://www.cslforum.org/.

0.3. Structure of This TRM

This TRM comprises four modules. The first module briefly describes the current status of CO_2 capture, transport and storage technology. The second module outlines ongoing activities, while the third module identifies technology needs and gaps that should be addressed over the next decade and beyond. The final module defines milestones to achieve commercialisation of CCS by 2020 and describes actions that need to be undertaken by governments, industry and other stakeholders to achieve these milestones.

MODULE 1: CURRENT STATUS OF CO_2 CAPTURE AND STORAGE TECHNOLOGY

1.1. Preamble – Sources of CO_2

Anthropogenic CO_2 is emitted into the atmosphere from:

- The combustion of fossil fuels for electricity generation;
- Industrial processes such as iron and steelmaking and cement production;
- Chemical and petrochemical processing, such as hydrogen and ammonia production;
- Natural gas processing;
- The commercial and residential sectors that use fossil fuels for heating;
- Agricultural sources; and
- Automobiles and other mobile sources.

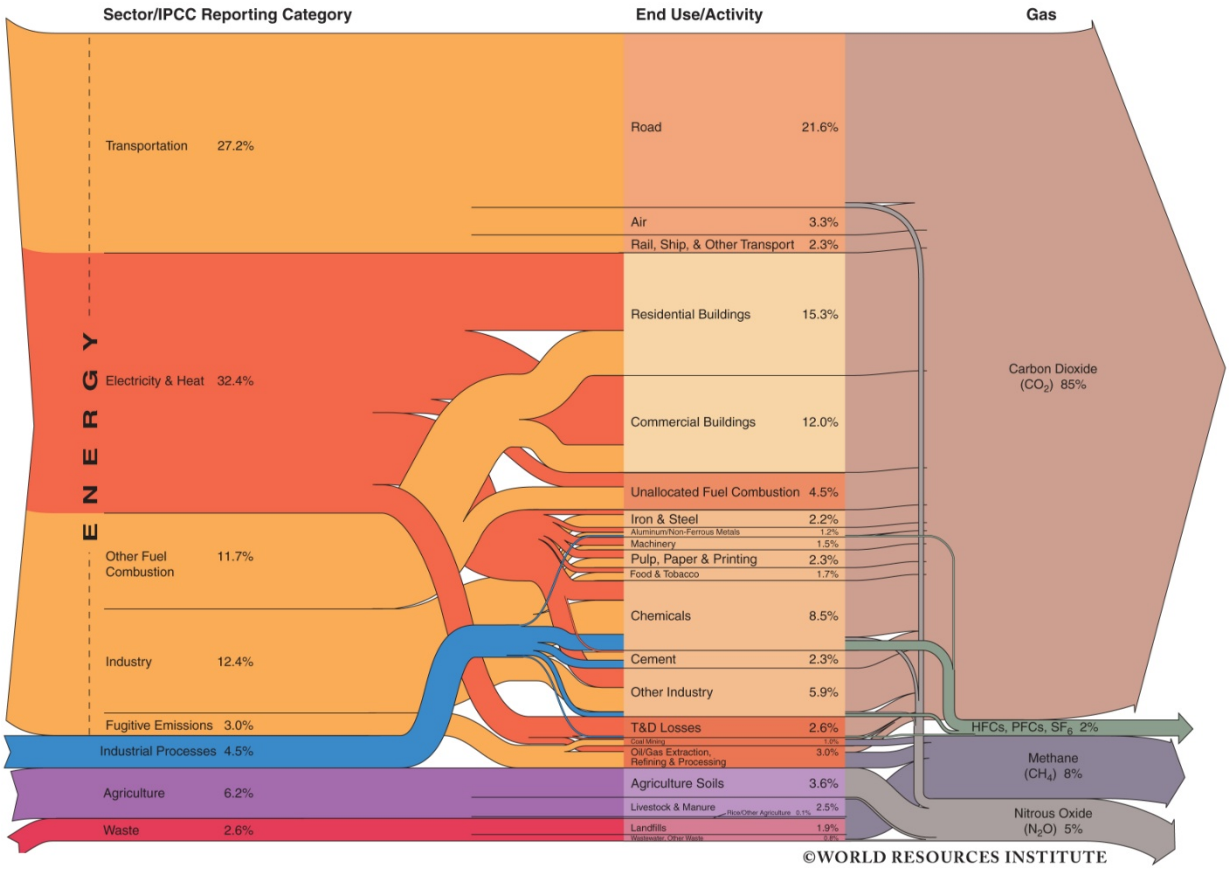


Figure 1. World emissions flow chart (World Resources Institute, 2005)

Due to the relative scale of emissions from stationary energy production there is an emphasis on power station emissions, although other emission sources from the energy and petrochemical industries, and industrial and transport applications are considered in the document.

To appreciate the volumes of CO_2 generated, a typical 500 megawatt (MWe) coal-fired power station will emit about 400 tonnes of CO_2 per hour while a modern natural gas-fired combined cycle (NGCC) plant of the same size will emit about 180 tonnes per hour of CO_2 in flue gases. The respective CO_2 concentrations in flues gases are about 14 percent (by volume) for a coal-fired plant and 4 percent CO_2 for an NGCC plant. By comparison, the concentration of CO_2 in the flue gas of a cement kiln can be up to 33 percent by volume.

As seen in Figure 1 for global emissions, stationary energy/electricity generation from fossil fuels is responsible for just more than one-third of all CO_2 emissions. The emissions from other, large industrial sources, including iron and steelmaking, natural gas processing, petroleum refining, petrochemical processing, and cement production, amount to about 25 percent of the global total. As the CO_2 emitted from such processes is typically contained in a few large process streams, there is good potential to capture CO_2 from these processes as well. The high CO_2 concentrations of some of these streams, such as in natural gas processing and clinker production in cement making, may provide ideal opportunities for early application of CO_2 capture technology.

The global iron and steel industry is assessing carbon capture in the iron ore reduction process (principally the blast furnace and electric arc furnace routes) as one of a number of pathways for a low carbon future. The European Ultra Low Carbon Dioxide Steelmaking program [ULCOS] http://www.ulcos.org/en/about_ulcos/home.php) is one such initiative that includes CCS as an element of technological developments.

The remaining anthropogenic CO_2 emissions are associated with transportation and commercial and residential sources. These are characterised by their small volume (individually) and the fact that, in the case of transportation, the sources are mobile. Capture of CO_2 from such sources is likely to be difficult and expensive, storage presents major logistical challenges, and collection and transportation of CO_2 from many small sources would suffer from small-scale economic distortions. A much more attractive approach for tackling emissions from distributed energy users is to use a zero-carbon energy carrier, such as electricity, hydrogen, or heat.

CO_2 capture is, at present, both costly and energy intensive. For optimal containment and risk-related reasons, it is necessary to separate the CO_2 from the flue gas so that concentrated CO_2 is available for storage. Cost depends on many variables including the type and size of plant and the type of fuel used. Currently, the addition of CO_2 capture can add 50–100 percent (or more) to the investment cost of a new power station (OECD/IEA, 2008).

CO_2 capture systems are categorised as post-combustion capture, pre-combustion capture, and oxyfuel combustion.

1.2. Capture of CO_2

1.2.1. Post-combustion Capture

Post-combustion capture refers to separation of CO_2 from flue gas after the combustion process is complete. The established technique at present is to scrub the flue gas with an amine solution (alkanolamines, 1.2.4.1 below). The amine-CO_2 complex formed in the scrubber is then decomposed by heat to release high purity CO_2 and the regenerated amine is recycled to the scrubber. Figure 2 is a simplified diagram of a coal-fired power station with post-combustion capture of CO_2.

Post-combustion capture is applicable to coal-fired power stations but additional measures, such as desulphurisation, will prevent the impurities in the flue gas from contaminating the CO_2 capture solvent. Two challenges for post-combustion capture are the large volumes of gas, which must be handled, requiring large-scale equipment and high capital costs, and the amount of additional energy needed to operate the process. The scale of CO_2 capture equipment needed and the consequent space requirements are illustrated in Figure 2.

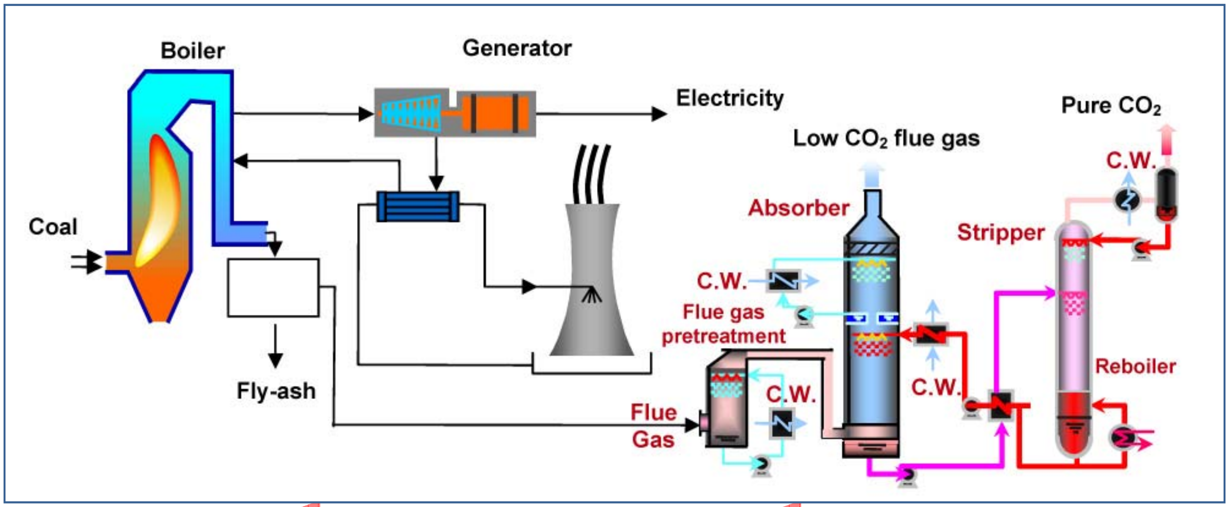


Figure 2. Coal-fired power station with post-combustion capture of CO_2 (courtesy of the Commonwealth Scientific and Industrial Research Organisation)

Figure 3. Photo montage of a 2x800 MW UK coal-fired power station with capture — shown behind the coal stockpiles (sourced from Imperial College, London and RWE Group)

1.2.2. Pre-combustion Capture

Pre-combustion capture increases the CO_2 concentration of the flue stream, requiring smaller equipment size and different solvents with lower regeneration energy requirements. The fuel is first partially reacted at high pressure with oxygen or air and, in some cases, steam, to produce carbon monoxide (CO) and hydrogen (H_2). The CO is reacted with steam in a catalytic shift reactor to produce CO_2 and additional H_2. The CO_2 is then separated and, for electricity generation, the H_2 is used as fuel in a combined cycle plant (see Figure 4). Although pre-combustion capture involves a more radical change to power station design, most elements of the technology are already well proven in other industrial processes. One of the novel aspects is that the fuel from the CO_2 capture step is primarily H_2. While it is expected that pure H_2 (possibly diluted with nitrogen [N_2]) can be burned in an existing gas turbine with little modification, this technology has not been demonstrated, although turbine testing has been carried out by manufacturers. In other industrial applications, pre-combustion has been identified as a technology for residual liquid-petroleum fuel conversion where H_2, heat, and power can be produced in addition to the CO_2 that needs to be captured.

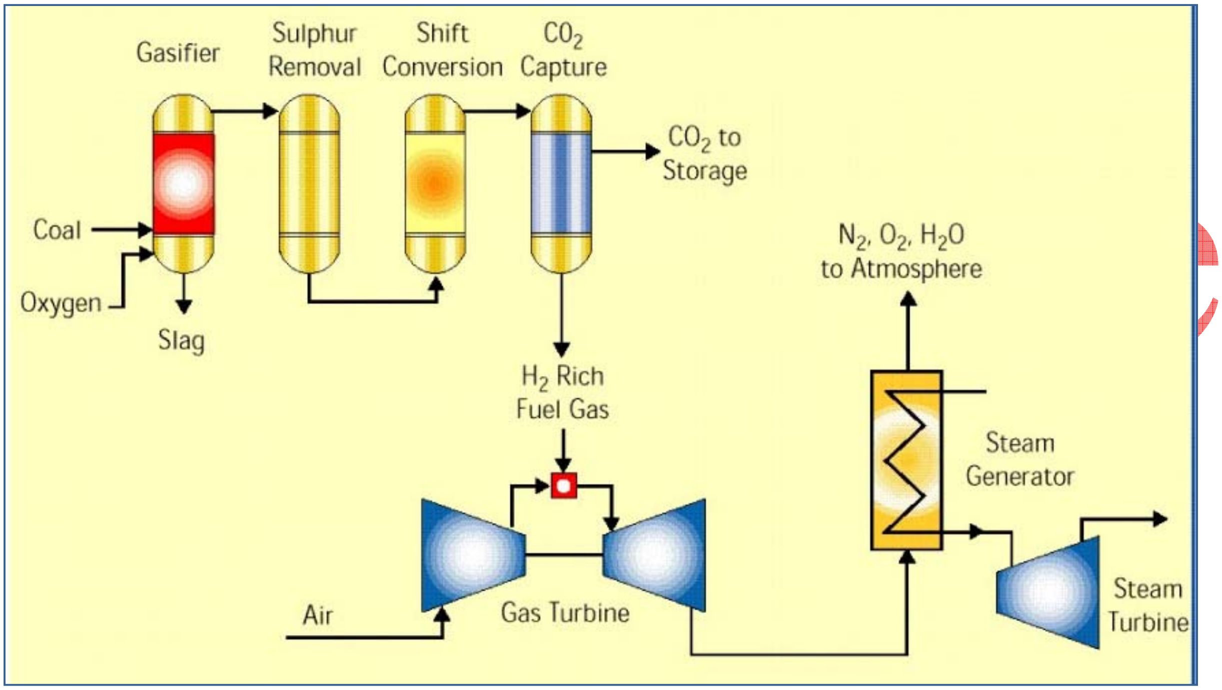


Figure 4. Coal-fired Integrated Gasification Combined Cycle (IGCC) process with pre-combustion capture of CO_2 (courtesy of the IEA GHG R&D Programme)

1.2.3. Oxyfuel Combustion

The concentration of CO_2 in flue gas can be increased by using pure or enriched oxygen (O_2) instead of air for combustion, either in a boiler or gas turbine. The O_2 would be produced by cryogenic air separation, which is already used on a large scale industrially, and the CO_2-rich flue gas would be recycled to the combustor to avoid the excessively high flame temperature associated with combustion in pure O_2. The advantage of oxyfuel combustion is that the flue gas contains a high concentration of CO_2, so the CO_2 separation stage is simplified. The primary disadvantage of oxyfuel combustion is that cryogenic O_2 is expensive, both in capital cost and energy consumption. Oxyfuel combustion for power generation has so far only been demonstrated on a small scale (up to about 30 MWth).

1.2.4. Type of Capture Technology

Some of the most widely used CO_2 separation and capture technologies are described below.

1.2.4.1. Chemical Solvent Scrubbing

The most common chemical solvents used for CO_2 capture from low pressure flue gas are alkanolamines. Alkanolamines are commonly used in post-combustion capture applications. The CO_2 reacts with the solvent in an absorption vessel. The CO_2-rich solvent from the absorber is passed into a stripping column where it is heated with steam to reverse the CO_2 absorption reaction.

CO_2 released in the stripper is compressed for transport and storage and the CO_2-free solvent is recycled to the absorption stage.

Amine scrubbing technology has been used for greater than 60 years in the energy, refining and chemical industries for removal of hydrogen sulphide (H_2S) and CO_2 from sour natural gas and reducing gases. Only a few facilities use amines to capture CO_2 from oxidising gases such as flue gas.

1.2.4.2. Physical Solvent Scrubbing

The conditions for CO_2 separation in pre-combustion capture processes are quite different from those in post-combustion capture. For example, the feed to the CO_2 capture unit in an IGCC process, located upstream of the gas turbine, would have a CO_2 concentration of about 35–40 percent and a total pressure of 20 bar or more. Under these pre-combustion conditions, physical solvents that result in a lower regeneration energy consumption through (for example) a lowering of the stripper pressure could be advantageous.

1.2.4.3. Adsorption

Certain high surface area solids, such as zeolites and activated carbon, can be used to separate CO_2 from gas mixtures by physical adsorption in a cyclic process. Two or more fixed beds are used with adsorption occurring in one bed while the second is being regenerated. Pressure swing adsorption (PSA) achieves regeneration by reducing pressure, while temperature swing adsorption (TSA) regenerates the adsorbent by raising its temperature. Electric swing adsorption (ESA), which is not yet commercially available, regenerates the adsorbent by passing a low-voltage electric current through it. PSA and TSA are used to some extent in hydrogen production and in removal of CO_2 from natural gas but generally are not considered attractive for large-scale separation of CO_2 from flue gas because of low capacity and low CO_2 selectivity.

1.2.4.4. Membranes

Gas separation membranes such as porous inorganics, nonporous metals (e.g., palladium), polymers, and zeolites can be used to separate one component of a gas mixture from the rest. Many membranes cannot achieve the high degrees of separation needed in a single pass, so multiple stages and/or stream recycling are necessary. This leads to increased complexity, energy consumption, and costs. Solvent-assisted membranes combine a membrane with the selective absorption of an amine, improving on both. This concept has been subject to long-term tests in a commercial test facility. Development of a membrane, capable of separating O_2 and N_2 in air could play an important indirect role in CO_2 capture. Lower cost O_2 would be important in technologies involving coal gasification and in oxyfuel combustion. Much development and scale-up is required before membranes could be used on a large scale for capture of CO_2 in power stations.

1.2.4.5. Cryogenics

CO_2 can be separated from other gases by cooling and condensation. While cryogenic separation is now used commercially for purification of CO_2 from streams having high CO_2 concentrations (typically >90 percent), it is not used for more dilute CO_2 streams because of high-energy requirements. In addition, components such as water must be removed before the gas stream is cooled to avoid freezing and blocking flow lines.

1.2.4.6. Other Capture Processes

One radical but attractive technology is chemical looping combustion, in which direct contact between the fuel and combustion air is avoided by using a metal oxide to transfer oxygen to the fuel in a two-stage process. In the first reactor, the fuel is oxidised by reacting with a solid metal oxide, producing a mixture of CO_2 and H_2O. The reduced solid is then transported to a second reactor where it is re-oxidised using air. Efficiencies comparable to those of other natural gas power generation options with CO_2 capture have been estimated. The major issue is development of materials able to withstand long-term chemical cycling.

THE EFFECT OF FUEL TYPE

The presence of fuel contaminants and specific combustion products impose additional constraints on the choice and operation of CO_2 control technology. With coal-fired systems, particulates can erode turbine blades in IGCC plants, contaminate solvents and foul heat exchangers in absorption processes, and foul membranes or sorbents in the new capture processes. Sulphur and nitrogen compounds must also be reduced to low levels before CO_2 capture because these impurities tend to react with amines to form heat stable salts, and may interact with membrane materials or sorbents to reduce the separation or capture efficiency. In contrast, natural gas and its combustion products are much more benign and tend to create fewer problems for all potential CO_2 capture options. Current work on "ultra-clean coal" products aims to address impurity and particulate issues so that coal-water mixtures can be used directly in reciprocating and turbine power generation systems.

RETROFIT APPLICATION

Repowering of existing coal-fired power stations has produced extended lifetimes and, in some cases, substantially improved efficiencies. There is potential for CO_2 capture to be retrofitted to existing plants as a component of a repowering project, particularly as plant downtime and major works would be required during repowering. This potential, however, may be limited by physical site conditions and proximity to CO_2 transport facilities and storage sites. Taking into account capital cost, loss in power station efficiency, and generation loss penalties, it is estimated that retrofitting an existing power station with CO_2 capture would cost 10 to 30 percent more than incorporating CO_2 capture into a new power station (McKinsey, 2008).

1.2.5. Further Work Required

The capture stage is the most important in determining the overall cost of CCS. Cost reductions of solvent absorption systems, new separation systems, new ways of deploying existing separations, and new plant configurations to make capture easier and less costly can deliver incremental cost decreases. However, novel approaches, such as re-thinking the power generation process, are needed if substantial reductions in the cost of capture are to be achieved.

1.3. CO_2 Transmission/Transport

Once captured and compressed, CO_2 must be transported to a long-term storage site. In this report, the words “transport” and “transmission” are used to describe movement of CO_2 from capture to storage site, in order to distinguish from the wider concept of transport (i.e., movement of goods or people by vehicles). In principle, transmission may be accomplished by pipeline, marine tankers, trains, trucks, compressed gas cylinders, as a CO_2 hydrate, or as solid dry ice. However, only pipeline and tanker transmission are commercially reasonable options for the large quantities of CO_2 associated with centralised collection hubs or point source emitters such as power stations of 500 MWe capacity or greater. Trains and trucks are used in some present pilot studies (Schwarze Pumpe project, Vattenfall 2009) and may be appropriate for small volumes of CO_2 over short distances.

1.3.1. Pipelines

Pipelines have been used for several decades to transmit CO_2 obtained from natural underground or other sources to oil fields for enhanced oil recovery (EOR) purposes. More than 25 million tonnes of CO_2 ($MtCO_2$) per year are transmitted through more than 5650km of high-pressure CO_2 pipelines in North America. The Weyburn pipeline, which transports CO_2 from a coal gasification plant in North Dakota, USA, to an EOR project in Saskatchewan, Canada, is the first demonstration of large-scale integrated CO_2 capture, transmission, and storage. Eventually, CO_2 pipeline grids, similar to those used for natural gas transmission, will be built as CCS becomes widely deployed. Figure 5 indicates the likely range of costs for the transmission of CO_2 through on-shore and off-shore pipelines.

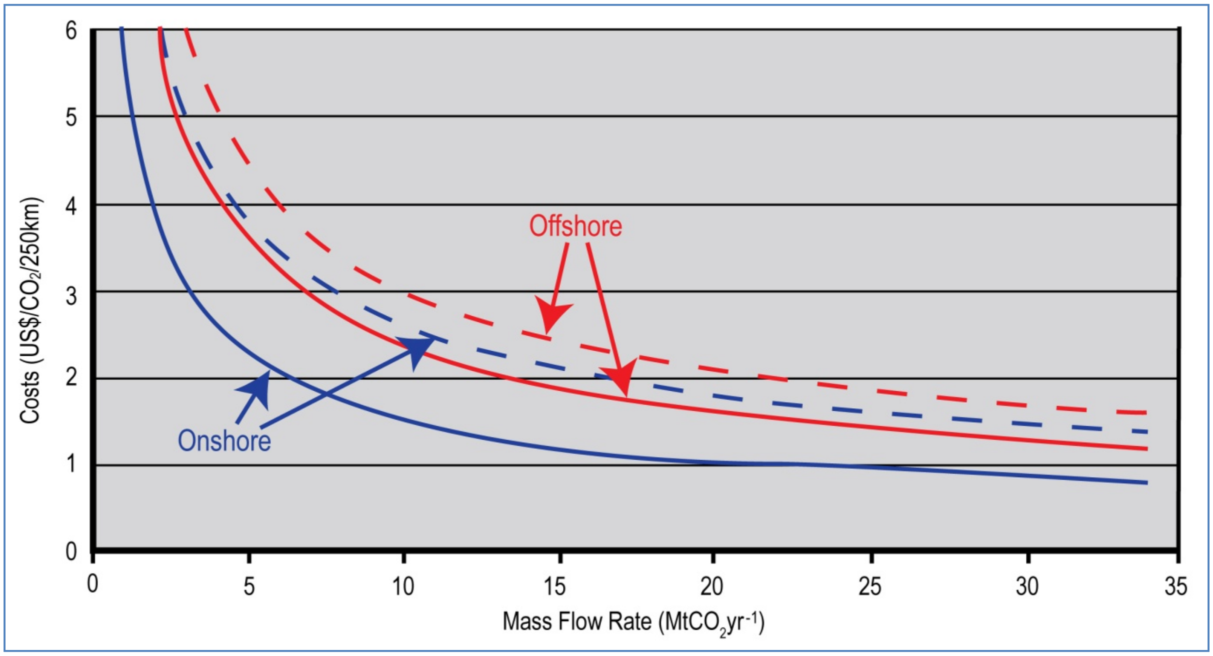


Figure 5. Range of CO_2 transport costs for on-shore and off-shore pipelines per 250 km. Solid lines show low range values and dotted lines high range values (Source: OECD/IEA, 2008)

1.3.2. Ship Tankers

Large-scale tanker transport of CO_2 from capture sites located near appropriate port facilities may occur in the future (smaller tankers in the scale of 1,500m^3 have been operating in the North Sea area for more than 10 years). The CO_2 would be transported in marine vessels such as those currently deployed for LNG/LPG transport as a pressurised cryogenic liquid (at high pressure/low temperature conditions). This would require relatively high purity CO_2. Ships offer increased flexibility in routes and they may be cheaper than pipelines for off-shore transportation, particularly for longer distances. It is estimated that the transport of 6MtCO_2 per year over a distance of 500km by ship would cost about 10US$/t$CO_2$, while transporting the same 6MtCO_2 a distance of 1,250km would cost about 15US$/t$CO_2$ (OECD/IEA 2008).

1.4. Storage of CO_2

1.4.1. General Considerations

Storage of CO_2 must be safe, permanent, and available at a reasonable cost, conform to appropriate national and international laws and regulations, and enjoy public confidence. The Intergovernmental Panel on Climate Change's Special Report on Carbon Dioxide Capture and Storage (2005) provides a thorough grounding in all aspects of CCS, with a focused discussion of storage in Chapter 5 (IPCC, 2005).

The previous Road Map noted that captured CO_2 can be stored:

- In certain types of geological formations;
- Through mineralization and industrial use; and possibly; and
- By injecting it into the ocean.

Each option is reviewed below.

1.4.2. Geologic Storage

Most of the world's carbon is held in geological formations: locked in minerals, in hydrocarbons, or dissolved in water. Naturally occurring CO_2 is frequently found with petroleum accumulations, having been trapped either separately or together with hydrocarbons for millions of years.

Subject to specific geological properties, several types of geological formations can be used to store CO_2 (Figure 6). Of these, deep saline-water saturated formations, depleted oil and gas fields, and unmineable coals have the greatest potential capacity for CO_2 storage. CO_2 can be injected and stored as a supercritical fluid in deep saline formations and depleted oil and gas fields, where it migrates, like other fluids (water, oil, gas) through the interconnected pore spaces in the rock. Supercritical conditions for CO_2 occur at 31.1°C and 7.38 MPa, which occurs approximately 800m below surface level where it has properties of both a gas and a liquid and is 500–600 times more dense (up to a density of about 700kg/m^3) than at surface conditions, while remaining more buoyant than formation brine. CO_2 can also be injected into unmineable coal beds where it is stored by adsorption onto the coal surface, sometimes enhancing coal bed methane production.

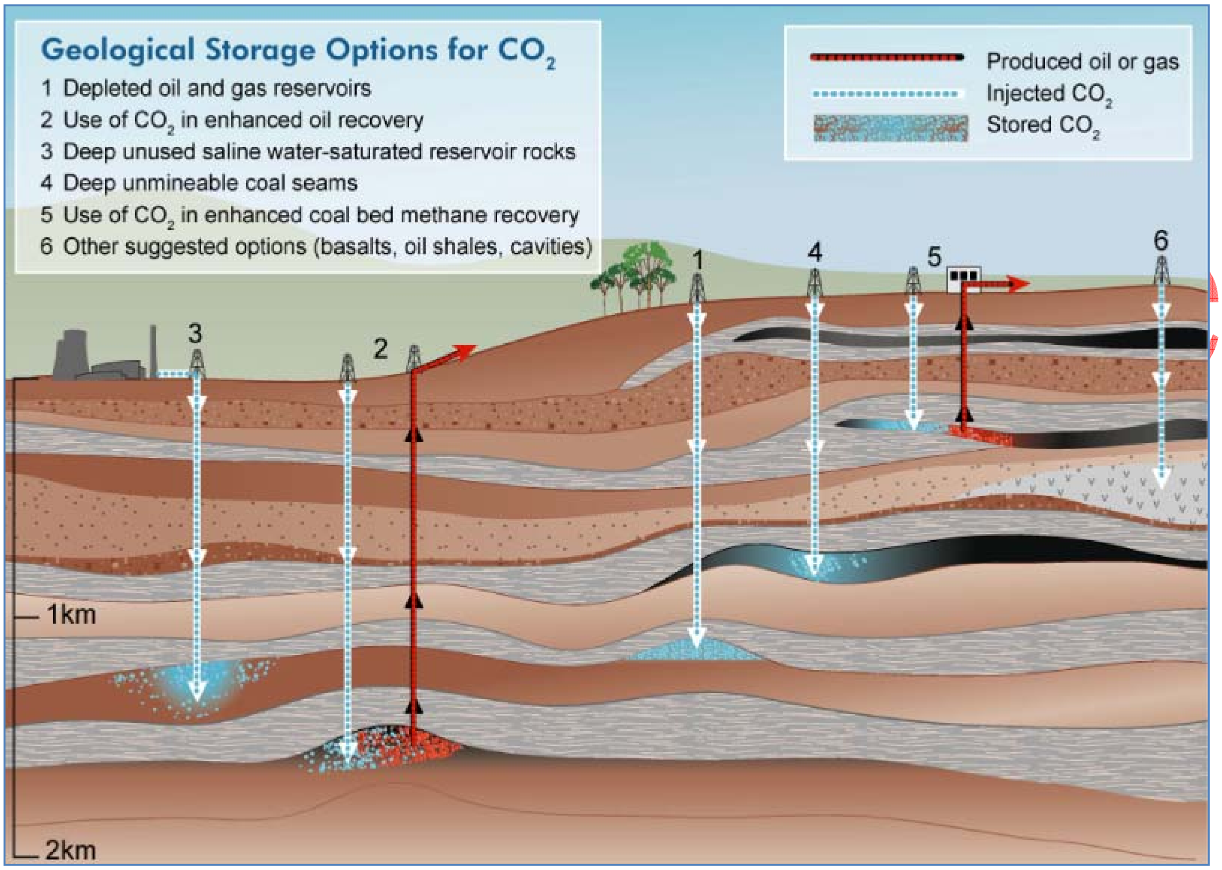


Figure 6. Geological options for CO_2 storage (courtesy of the Cooperative Research Centre for GHG Technologies)

1.4.2.1. Deep Saline Formations

Deep saline formations provide by far the largest potential volumes for geological storage of CO_2. These brine-filled sedimentary reservoir rocks (e.g., sandstones) are found in sedimentary basins and provinces around the world, although their quality and capacity to store CO_2 varies depending on their geological characteristics. Based on crude estimates, the total CO_2 storage capacity of these formations is sufficient to store many decades of CO_2 production. To be suitable for CO_2 storage, saline formations need to have sufficient porosity and permeability to allow large volumes of CO_2 to be injected in a supercritical state at the rate that it is supplied, and be overlain by an impermeable cap rock, or seal, to prevent CO_2 migration into overlying fresh water aquifers, other formations, or the atmosphere.

The chief advantages of deep saline formations for CO_2 storage are their widespread nature and potentially huge available volumes.

The Sleipner project in the Norwegian sector of the North Sea was the first demonstration of CO_2 storage in a deep saline formation designed specifically in response to climate change mitigation. Injection of approximately one million tonnes of CO_2 per year (captured from a natural gas stream) into the Utsira Formation at a depth of about 1,000m below the sea floor, began in 1996. The CO_2 is being monitored through an international project established by StatoilHydro with the IEA GHG R&D Programme (StatoilHydro, 2008). Following Sleipner, several other large-scale deep saline formation storage projects have also come on line, including:

- The In Salah Gas project in Algeria, where, since 2004, 1.2 million tonnes of CO_2 per year have been injected into the aquifer portion of the gas reservoir at a depth of 1,800m (StatoilHydro, 2008); and
- The Snøhvit LNG project in the Barents Sea, where, since 2008, 700,000 tonnes of CO_2 per year have been stored in a saline formation 2,500m beneath the sea floor (StatoilHydro, 2008).

Both projects have associated monitoring programs.

1.4.2.2. Depleted Oil and Gas Reservoirs

Oil and gas reservoirs are a subset of saline formations and therefore generally have similar properties, that is, a permeable rock formation (reservoir) with an impermeable cap rock (seal). The reservoir is that part of the saline formation that is generally contained within a structural or stratigraphic closure (e.g., an anticline or dome), and was therefore able to physically trap and store a concentrated amount of oil and/or gas.

Conversion of many of the thousands of depleted oil and gas fields for CO_2 storage should be possible as the fields approach the end of economic production. There is high certainty in the integrity of the reservoirs with respect to CO_2 storage, as they have held oil and gas for millions of years. However, a major drawback of oil and gas reservoirs compared with deep saline aquifers is that they are penetrated by many wells of variable quality and integrity, which themselves may constitute leakage paths for the stored CO_2. Care must be taken to ensure that exploration and production operations have not damaged the reservoir or seal (especially in the vicinity of the wells), and that the seals of shut-in wells remain intact. Costs of storage in depleted fields should be reasonable as the sites have already been explored, their geology is reasonably well known, and some of the oil and gas production equipment and infrastructure could be used for CO_2 injection.

The major difference between depleted oil fields and depleted gas fields is that many oil fields contain large volumes of unproduced oil after production has ceased, whereas most of the gas in gas fields can be produced. Depleted gas fields possess significant storage capacity due to their large size and high recovery factor (>80 percent), as opposed to oil reservoirs whose recovery factor can be as low as 5 percent, but globally, can range from 25–65 percent. EOR methods, using water, natural gas, solvents, N_2, or CO_2, are often employed to extract more of the oil after primary production has waned (see section 1.4.1). CO_2 injection should therefore trigger additional production which may help offset the cost of CO_2 storage. In this sense, storage in depleted oil reservoirs will involve an element of EOR, while CO_2 injection into depleted gas reservoirs may not result in additional gas production.

It is important to note that the storage capacity of depleted oil and gas fields is small relative to the potential capacity of deep saline formations and to CO_2 emissions. However, they do present an early opportunity for CO_2 storage, particularly where associated with EOR. Deep saline formations around, beneath, or above depleted oil and gas fields could be used for CO_2 storage.

1.4.2.3. Unmineable Coal Beds

Coal beds below economic mining depth could be used to store CO_2. CO_2 injected into unmineable coal beds is adsorbed onto the coal and stored as long as the coal is not mined or otherwise disturbed. Methane, which occurs naturally with coal, will be displaced when CO_2 is injected and can result in enhanced coal bed methane (ECBM) production (discussed further in section 3.2.4). Because methane is also a GHG with a radiative power 21 times stronger than CO_2, it should be captured and used, otherwise, its release into the atmosphere will have worse effects than not storing CO_2 in coals in the first place.

CO_2 storage in coal is limited to a relatively narrow depth range, between 600m and 1,000m, and less than 1,200m. Shallow beds less than 600m deep have economic viability and beds at depths greater than 1,000m have decreased permeability for viable injection. A significant problem with injection of CO_2 into coal beds is the variable, and sometimes very low, permeability of the coal, which may require many wells for CO_2 injection. Coal may also swell with adsorption of CO_2 which will further reduce existing permeability. Low permeability can, in some cases, be overcome by fracturing the coal formation; however, there is the risk of unintended fracturing of the cap rock layer, increasing the potential for CO_2 migration out of the intended storage zone. Another drawback of CO_2 storage in coals is that at shallow depths they may be within the zone of protected groundwater, which is defined as water with salinity below 4,000 to 10,000 mg/L, depending on jurisdiction. In such cases, the depth interval of coals potentially suitable for CO_2 storage will be further reduced.

Storage in unmineable coal beds has and is being investigated in several pilot projects worldwide (National Energy Technology Laboratory, 2008).

1.4.2.4. Other Geological Storage Options

Other geological CO_2 storage options include injection into basalt, oil shale, salt caverns and cavities, geothermal reservoirs, and lignite seams, as well as methano-genesis in coal seams. These options are in early stages of development, and appear to have limited capacity except, possibly, as niche opportunities for emissions sources located far from the more traditional, higher capacity storage options.

1.4.3. Mineralisation

Nature's way of geologically storing CO_2 is the very slow reaction between CO_2 and naturally occurring minerals, such as magnesium silicate, to form the corresponding mineral carbonate. Dissolution of CO_2 in water forms carbonic acid (H_2CO_3), a weak acid:

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H+ \leftrightarrow CO_3^{2-} + 2H^+ \qquad [1]$$

The carbonic acid can then react with the calcium, magnesium, and iron in carbonate and silicate minerals such as clays, micas, chlorites, and feldspars to form carbonate minerals such as calcite (IPCC, 2005):

$$\text{e.g., } Ca^{2+} + H_2CO_3 \rightarrow CaCO_3 + 2H^+ \qquad [2]$$

Of all forms of carbon, carbonates possess the lowest energy, and are therefore the most stable. CO_2 stored as a mineral carbonate would be permanently removed from the atmosphere. Research is underway to increase the carbonation rate, however, the mass of mineral that would have to be quarried would be many times the mass of CO_2 captured.

A novel example of mineralisation undergoing pilot-scale trials is the chemical conversion of refining wastes, such as bauxite residue (red mud), by combining with CO_2. While ideally suited to lower CO_2 volumes, the process addresses CO_2 storage needs while reducing the environmental issues associated with the caustic form of the residue if stored as a carbonate when reacted with CO_2.

1.4.4. Deep Ocean Storage

Two types of CO_2 injection into the ocean have been considered in the past. In the first, the CO_2 would be injected at depth, to dissolve in the seawater. In the second, concentrated CO_2 in liquid or solid hydrate form would be isolated either on or under the sea bed. The deep oceans have, in principle, capacity for retaining CO_2 for hundreds of years. But these storage options are highly unlikely to be used.

Increased acidity near the point of CO_2 injection is a primary environmental concern. Due to these effects, the International Maritime Organisation stated that CO_2 can only disposed of in a sub-seabed geological formation (International Maritime Organisation, 2007).

Disposal into the water-column and on the seabed may be dealt with in the future but, based on current understanding this report does not consider deep ocean storage of CO_2 further.

1.4.5. Security of Storage

Natural deep subsurface accumulations of CO_2 occur in many sedimentary basins around the world and, like oil and gas, can be a valuable, extractable resource. Pure CO_2 is a commercial commodity with widespread application in the food and beverage industry. These accumulations provide evidence that CO_2 can be and has been stored over millions of years — they are natural analogues for understanding the geological storage of captured GHGs.

1.4.5.1. Natural Analogues of CO_2 Storage

CO_2 accumulations occur naturally in geological formations, often in association with hydrocarbons. Core sampling of these natural accumulations provides information on the geochemical reactions that occur between stored CO_2 and the rock. Evidence of low rates of leakage has been found at some natural sites, which provides a laboratory to study environmental and safety implications, as well as measurement, monitoring and verification (MMV) techniques. The fact that CO_2 has been securely stored for millions of years in places like commercial gas fields (Miyazaki et al., 1990) is important in understanding the fate of CO_2 stored underground.

1.4.5.2. Commercial Analogues of CO_2 Storage

Transportation and certain aspects of CO_2 storage are similar in many respects to natural gas transportation and storage. Natural gas is widely transported around the world via pipelines and ships, and is stored in several hundred sites around the world, some for more than 60 years, in geological formations to ensure constant supply. While small in comparison to the volumes of CO_2 to be stored as a result of CCS, significant quantities of CO_2 are routinely transported by pipeline in association with EOR projects (IPCC, 2005). Operating procedures and safety standards have been developed, and there is increasing experience with underground injection of CO_2. Another commercial analogue is disposal of acid gas (a mixture of H_2S and CO_2 separated from sour natural gas), practiced at more than 70 sites in North America for more than 2 decades.

With gas re-injection, either for storage or EOR, reservoir over-pressurisation could activate or cause fractures and lead to leakage: application of engineering techniques, in response to rock properties, and understanding fluid systems, should prevent this from occurring. The greatest concern about CO_2 storage in oil and gas fields is the integrity of the many wells drilled during the exploration and production phases of the operation. Cement degradation, casing corrosion, or damage to the formation near the well could result in leakage. But as in standard oilfield practise, there are mitigation strategies that can be put in place to ensure well integrity.

1.4.5.3. Understanding Leakage

Naturally occurring CO_2 leakage does occur in tectonically active areas and near volcanoes. These sites can show us the effect of leakage on the geosphere and biosphere. Sites selected for underground storage for CO_2 will:

- Undergo rigorous analysis to ensure they are capable of permanent storage; and
- Have a rigorous detection, monitoring, and verification of storage program in place to track the migration of CO_2 in the storage formation.

In the unlikely event that underground leakage pathways are established, the CO_2 could migrate upward and could mix with water in overlaying aquifers or even reach the surface. Trapping mechanisms such as mineralisation, dissolution, and residual trapping occurring along the migration pathway will result in only a small fraction of the injected CO_2 having the potential to reach the surface and, should a leak be detected, remediation actions would be implemented.

1.4.5.4. Risk Assessment

Extensive experience exists in the oil and gas industry for gas transport and injection, including CO_2. As such, those risks are well understood. Modeling studies assist in assessing the long-term behaviour and migration of stored CO_2 although field data to validate these models is still lacking. Comprehensive system approaches for risk assessment are being developed and applied as part of all capture, transport, and storage programs. Monitoring is an essential factor in mitigating risk.

Environmental impact assessments incorporating risk assessments and methods for managing risks are required where new operations or significant changes in existing operations are planned. A solid technological foundation through technology developments, demonstrations, and risk assessment methodologies will be needed in order to garner broad public acceptance as well as contribute to the creation of a sound regulatory framework for geological CO_2 storage.

1.5. Uses for CO_2

Commercially produced CO_2 is used for enhancing oil, gas, and coal bed methane production; biofixation; and for making industrial and food products. The total quantity of CO_2 that could be used will be much less than the total quantity that could be captured, but there is potential for research into new industrial uses of CO_2 or for CO_2 as a feedstock into other processes as discussed in 1.4.3.

1.5.1. Enhanced Oil and Gas Recovery (EOR and EGR)

Primary, conventional oil production techniques may only recover a small fraction of oil in reservoirs, typically 5–15 percent (Tzimas et al., 2005), although initial recovery from some reservoirs may exceed 50 percent. For the majority, secondary recovery techniques such as water flooding can increase recovery to 30–50 percent (Tzimas et al., 2005). Tertiary recovery techniques such as CO_2 injection, which is already used in several parts of the world, mostly in the Permian Basin in the United States of America, pushes recovery even further. At present, most of the CO_2 used for EOR is obtained from naturally occurring CO_2 fields or recovered from natural gas production. Because of the expense, CO_2 is recycled as much as possible throughout the EOR process but the CO_2 left in the reservoir at the end of recovery is for all intents and purposes permanently stored.

There are currently more than 100 active CO_2-EOR projects worldwide, the vast majority in the USA. The largest of these, the Dakota Gasification Plant in North Dakota, USA, captures 2.8 million tonnes of CO_2 annually and transports it 330 kilometers by pipeline to the Weyburn EOR project in Saskatchewan, Canada. This was the first major project designed to demonstrate the long-term effectiveness of CO_2 capture coupled with EOR. Currently, about 3.2 million tonnes of CO_2 are injected for EOR at the Cenovus and Apache fields at Weyburn each year, with approximately 35 million tonnes of CO_2 expected to be stored over the course of the project (Total Petroleum Technology Research Centre, 2008).

Enhanced gas recovery is different because it is possible to produce almost all of the original gas in place through primary production techniques. However, injection of CO_2 into a producing gas reservoir will help maintain reservoir pressure and increase the rate of gas production. Because of rapid CO_2 expansion in the reservoir, breakthrough will occur rather rapidly and CO_2 will be produced along with the gas, necessitating separation of the CO_2 from the natural gas, in a way mimicking the current operations at Sleipner and In Salah, and also at all acid gas disposal operations in North America. Initially, when CO_2 concentrations in the produced gas are low, it may be possible to separate and re-inject the CO_2, however, the CO_2 concentration will increase with time and eventually separation and re-injection will not be economically feasible. At this point gas production will end and CO_2 will be stored in the depleted reservoir. The costs associated with the need of separating the CO_2 from the produced gas will most likely not justify enhanced gas recovery operations.

CO_2 can be injected into methane-saturated coal beds and will preferentially displace adsorbed methane, thereby increasing methane production. Coal can adsorb about twice as much CO_2 by volume as methane, and the adsorbed CO_2 is permanently stored. Several enhanced coal bed methane recovery pilot or demonstration projects have been conducted worldwide, including in the USA, China, and Europe.

1.5.2. Biofixation

Biofixation is a technique for production of biomass using CO_2 and solar energy, typically employing microalgae or cyano-bacteria. Horticulture (in glass houses) often uses CO_2 to enhance the growth rates of plants by artificially raising CO_2 concentrations.

Depending on the use of the material grown in this way, there may be some climate change benefits. For example, microalgae can be grown in large ponds to produce biomass, which can then be converted into gas or liquid fuels, or high value products such as food, fertilisers, or plastics. However, the demand for high value products is currently insufficient to justify large-scale capture of CO_2; the carbon is only fixed for a short time and there are challenges associated with the resource and space requirements to allow large-scale CO_2 fixation.

1.5.3. Industrial Products

CO_2 captured from ammonia (NH_3) reformer flue gas is now used as a raw material in the fertiliser industry for the manufacture of urea, and purified CO_2 is used in the food industry. Possible new uses include the catalytic reduction of light alkanes to aromatics using CO_2, formation of alkylene polycarbonates used in the electronics industry, and the production of dimethylcarbonate as a gasoline additive.

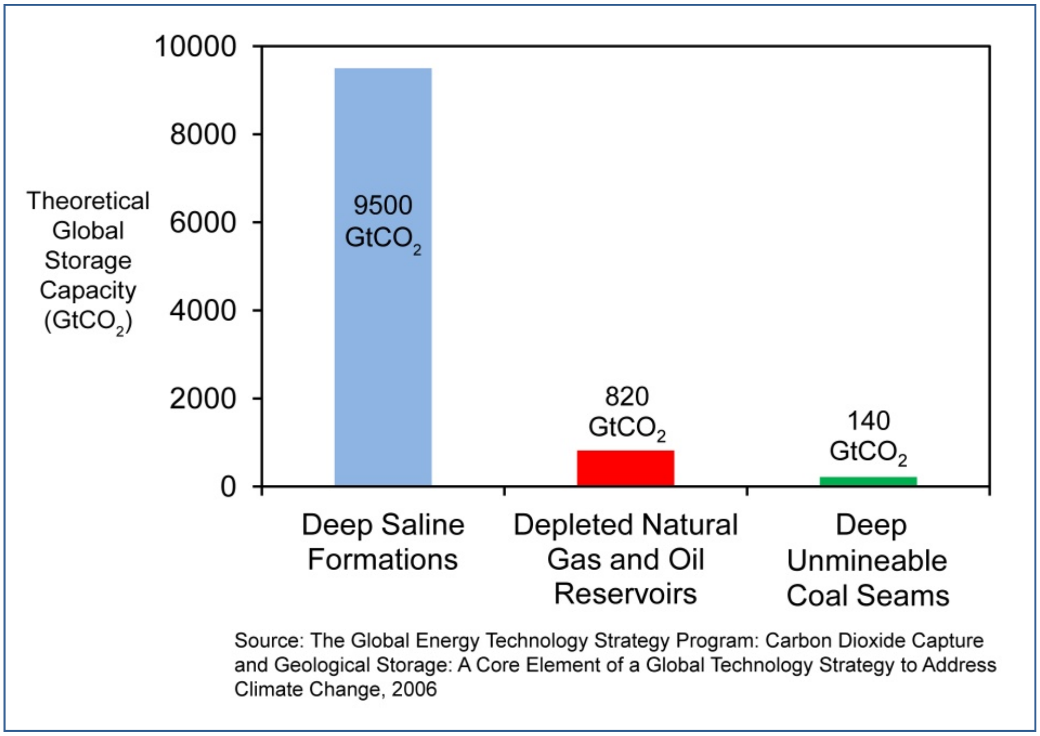
Because CO_2 is thermodynamically stable, significant energy is needed in its conversion for use as a chemical raw material. The additional energy requirement and cost may preclude its use as a chemical raw material in all but a few niche markets. CO_2 used for producing industrial products will be normally released within a few months or years. To successfully mitigate the risk of climate change, CO_2 needs to be stored for thousands of years (IPCC, 2005).

1.6. The Potential for CO_2 Storage

Economically, once the more profitable offsets for CO_2 injection have been exploited, the storage of CO_2 will need other cost drivers to ensure its financial viability such as a price on carbon. Storage of CO_2 in oil and gas reservoirs will have the advantage that the geology of reservoirs is well known and existing infrastructure may be adapted for CO_2 injection. The same does not apply to unmineable coal seams or storage in deep saline formations which collectively may be exposed to higher overall storage cost structures because of lack of offsets.

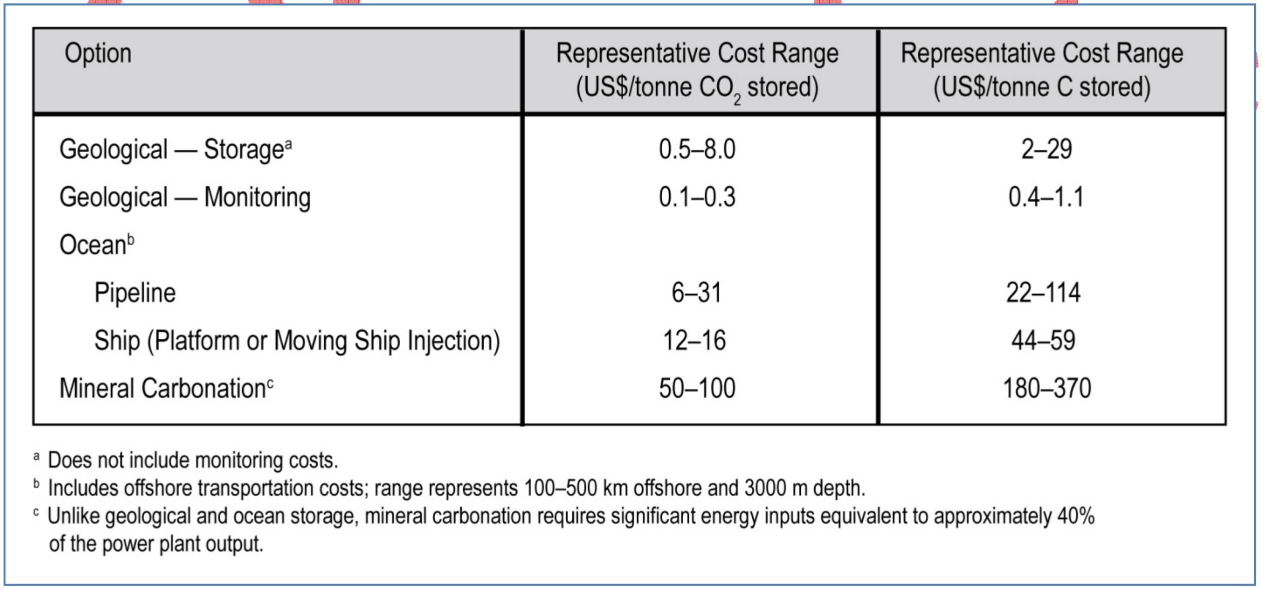
Figure 7 indicates the theoretical global storage capacity for deep saline formations, depleted oil and gas reservoirs, and unmineable coal seams. Note that these capacity estimates are broad indications only, with high ranges of uncertainty, and include non-economical options.

Many factors influence the costs of storage and these are very site-specific (e.g., the number of injection wells required, on-shore versus off-shore, and so on). However, the storage component of CCS is generally held to be the cheapest part of the process, in which the costs of capture dominate. Figure 8 (table) shows estimates of CO_2 storage costs.



Source: The Global Energy Technology Strategy Program: Carbon Dioxide Capture and Geological Storage: A Core Element of a Global Technology Strategy to Address Climate Change, 2006

Figure 7. The theoretical global storage capacity of CO_2



Option	Representative Cost Range (US$/tonne CO_2 stored)	Representative Cost Range (US$/tonne C stored)
Geological — Storage[a]	0.5–8.0	2–29
Geological — Monitoring	0.1–0.3	0.4–1.1
Ocean[b]		
Pipeline	6–31	22–114
Ship (Platform or Moving Ship Injection)	12–16	44–59
Mineral Carbonation[c]	50–100	180–370

[a] Does not include monitoring costs.
[b] Includes offshore transportation costs; range represents 100–500 km offshore and 3000 m depth.
[c] Unlike geological and ocean storage, mineral carbonation requires significant energy inputs equivalent to approximately 40% of the power plant output.

Figure 8. Estimates of CO_2 storage costs (Source: IPCC, 2005)

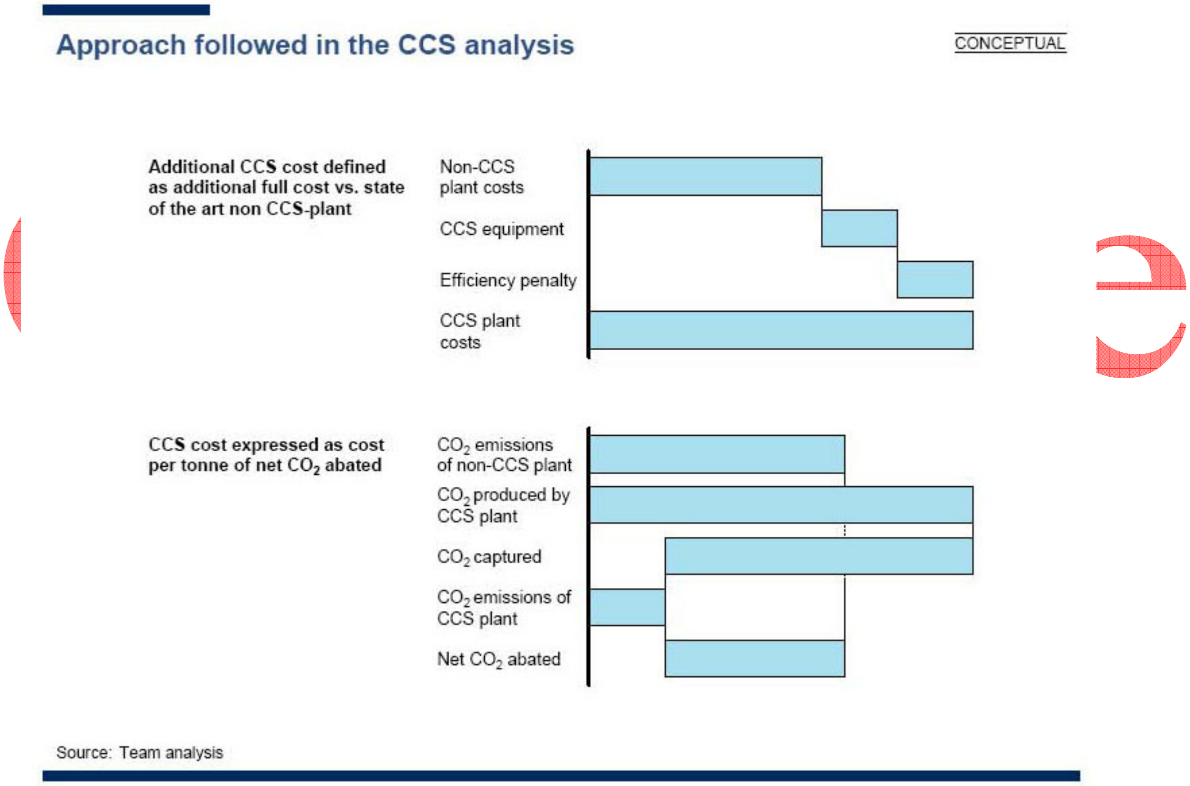
Power Station Performance and Costs: With and Without CO_2 Capture

IPCC, IEA, McKinsey & Company, and other organisations have evaluated the performance and costs of power generation options with and without CO_2 capture. These sources have been utilised in this TRM but it should be noted that a wide range of models, variables, units, and values are used across the CCS industry.

Electricity generation technologies considered in this section include supercritical pulverised coal fuel (PC), IGCC, and natural gas combined cycle (NGCC) plants. These power station types have been included in this analysis because they hold promise for CCS and there is a greater body of reliable information relating to these technology types. Other configurations may be considered in future revisions of this document.

Power Station Performance

Figure 9 shows the conceptual costs associated with the capture of CO_2 from power stations. The cost of CCS is defined as the additional full cost (i.e., including initial investments and ongoing operational expenditures) of a CCS power station compared to the costs of a state-of-the-art non-CCS plant, with the same net electricity output and fuel usage.



Source: Team analysis

Figure 9. The conceptual costs associated with CO_2 capture for power stations

Current studies indicate that a decrease of power station efficiency by 14 percentage points can occur with the addition of CO_2 capture (OECD/IEA, 2008). Most of this is attributable to the additional energy requirements for the capture process. The actual efficiency shortfalls vary significantly on a case-by-case basis with the key determinants being technology type and fuel type. These ranges are shown in Figure 10.

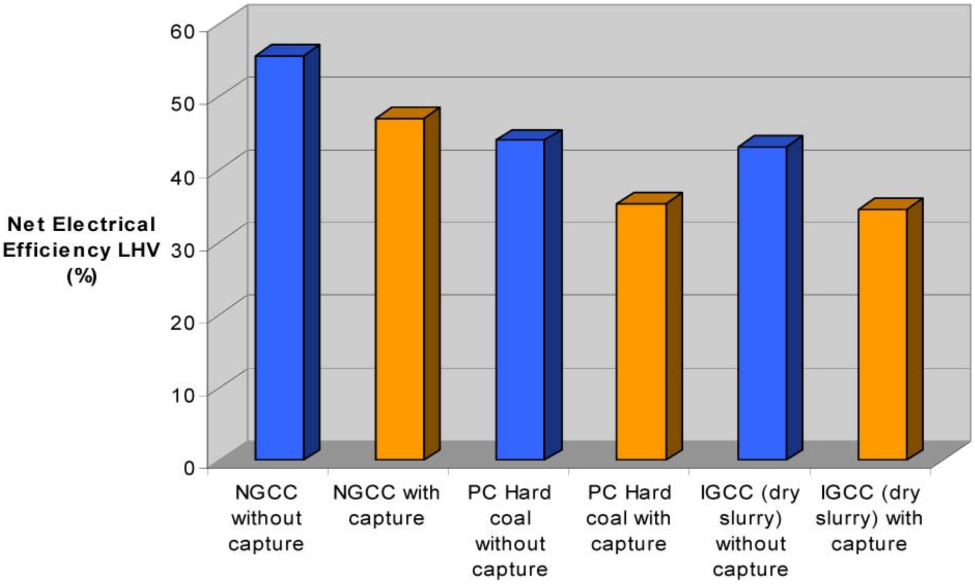


Figure 10. Power station generation efficiencies with and without the capture of CO_2 (Source: IEA GHG R&D Programme, 2007)

Economic modeling in the Global CCS Institute 2009 Strategic Analysis of the Global Status of CCS, which is summarized in Figure 11, determined that the cost of CCS for power generation, based on the use of commercially available technology, ranged from $62 to $112 per tonne of CO_2 avoided or $44 to $90 per tonne of CO_2 captured. The lowest cost of CO_2 avoided was at $62 per tonne of CO_2 for the oxyfuel combustion technology, while the highest cost at $112 per tonne of CO_2 for the NGCC with post-combustion capture. This compares with the lowest cost of captured CO_2 for the oxy-combustion and IGCC technologies at $44 per tonne of CO_2 and the highest of $90 per tonne of CO_2 for NGCC technologies. The metrics are determined for the reference site in the USA with fuel costs based on values typical for 2009.

Figure 11 also shows the percentage increase in costs that the application of CCS has over non-CCS facilities. For power generation, facilities that had the lowest cost increases were IGCC (39 percent), NGCC (43 percent), followed by oxyfuel combustion (55–64 percent) and PC supercritical (75–78 percent) technologies.

The application of CCS for First of a Kind (FOAK) industrial applications shows that cost of CO_2 avoided is lowest for natural gas processing ($18), and fertiliser production ($18) followed by cement production ($50) and blast furnace steel production ($52).

Table 1 enables comparisons to be made across industrial applications in regards to the percentage increase in costs arising from the application of CCS. The lowest cost increase is for natural gas processing (1 percent) followed by fertiliser production (3–4 percent). This is unsurprising given that these industries already have the process of capturing CO_2 as a part of their design. The production of steel (15–22 percent) and cement (36–48 percent) have the highest percentage cost increases with the application of CCS because the capture of CO_2 is not inherent in the design of these facilities.

The margin of error in comparative CCS technology economics, however, makes it difficult to select one generic technology over another based on the levelised cost of electricity (LCOE).

Projects employing different capture technologies may be viable depending on a range of factors such as location, available fuels, regulations, risk appetite of owners, and funding.

Cost reduction will occur through the progressive maturation of existing technology and through economies of scale as well as from technology breakthroughs with the potential to achieve step-reductions in costs. For example:

- Capital costs of capture equipment will decline 6–27 percent for power generation projects with implementation of lessons learned from FOAK projects. These reductions result in potential generation and capture capital cost savings of 3–10 percent and a resulting decrease in the LCOE of less than 5 percent.
- Process efficiency improvements both in the overall process and the energy penalty for CO_2 capture will result in significant savings. The introduction of technologies such as ITM for air separation for oxy-combustion, which reduces the auxiliary load and thus improves the overall efficiency, leads to a 10 percent decrease in the cost increase (LCOE basis) resulting from the implementation of CCS. Capital costs are reduced through the plant size decreasing to produce the same net output. The operating costs decrease through a reduction in the fuel required per unit of product.
- Industrial processes which currently include a CO_2 separation step (natural gas processing and ammonia production, for example) have greatly reduced incremental cost increase related to CCS deployment. Projects employing these processes can be considered as early movers of integrated systems. In this case the CO_2 separation costs are currently included in the process and do not represent an additional cost.
- Pipeline networks, which combine the CO_2 flow from several units into a single pipeline, can reduce cost of CO_2 transport by a factor of three.
- The initial site finding costs and characterisation represent a significant risk to the project and can increase storage costs from US$ 3.50/tonne CO_2 to US$ 7.50/tonne CO_2, depending on the number of sites investigated.
- Reservoir properties, specifically permeability, impact the ease that CO_2 can be injected into the reservoir and the required number of injection wells. Reservoirs with high permeability can reduce storage cost by a factor of two over reservoirs with lower permeability.

Figure 11. Summary of economic assessment of CCS technologies

Notes:

		POWER GENERATION				INDUSTRIAL APPLICATIONS			
		PC Supercritical & Ultra Supercritical*[1]	Oxy-combustion Standard & ITM*[1]	IGCC	NGCC	Blast Furnace Steel Production	Cement Production	Natural Gas Processing	Fertilizer Production
	Dimensions	US$/ MWh	US$/ MWh	US$/ MWh	US$/ MWh	US$/tonne steel	US$/tonne cement	US$/GJ natural gas	US$/tonne ammonia
Levelised Cost of Production	Without CCS*[2]	76–79	76–79*[3]	96	78	350–500	66–88	4–9	270–300
	With CCS FOAK*[3]	136–138	120–127	134	112	80	32	0.053	10
	With CCS NOAK*[4]	134–136	118–125	132	111	72	30	0.053	10
	% Increase over without CCS*[5]	75–78%	55–64%	39%	43%	15–22%	36–48%	1%	3–4%
Cost of CO_2 Avoided*[6] (\$/tonne CO_2)	FOAK	87–91	62–70	81	112	52	50	18	18
	NOAK	84–88	60–68	78	109	47	47	18	18
Cost of CO_2 Captured (\$/tonne CO_2)	FOAK	56–57	44–51	44	90	52	50	18	18
	NOAK	54–55	42–49	42	87	47	47	18	18

FOAK = First of a Kind; NOAK = Nth of a Kind

*1: The ultra-supercritical and ITM technologies are currently under development and are not commercially available. These technologies represent future options with the potential for increasing process efficiencies and to reduce costs.

*2: Without CCS the cost of production for industrial processes are typical market prices for the commodities.

*3: Oxyfuel combustion systems are not typically configured to operate in an air-fired mode. Therefore, oxyfuel combustion without CCS is not an option. The values here are PC without CCS, to be used as a reference for calculating the cost of CO_2 avoided.

*4: For industrial processes, the levelised cost of production is presented as cost increments above current costs.

*5: Expressed with respect to current commodity prices for industrial processes.

*6 The reference plant for the coal-fired technologies cost of CO_2 avoided is the PC supercritical technology. As discussed, in select previous studies, the cost of CO_2 avoided has been calculated with the reference plant selected as the similar technology without CCS. For IGCC, under this assumption, the FOAK and NOAK costs of CO_2 avoided are \$61/tonne and \$59/tonne, respectively.

Source: Global CCS Institute 2009, Strategic Analysis of the Global Status of Carbon Capture and Storage, Report 2 Economic Assessment

MODULE 2: ONGOING ACTIVITIES IN CO2 CAPTURE AND STORAGE

2.1. Introduction

This module summarises ongoing activities on the capture and storage of CO_2. Figure 12A shows Active or Planned Large-scale Integrated Projects by Capture Facility, Storage Type, and Region; Figure 12B shows Active or Planned Large-scale Integrated Projects in North America by Capture Facility and Storage Type; and Figure 12C shows Active or Planned Large-scale Integrated Projects in Europe by Capture Facility and Storage Type.

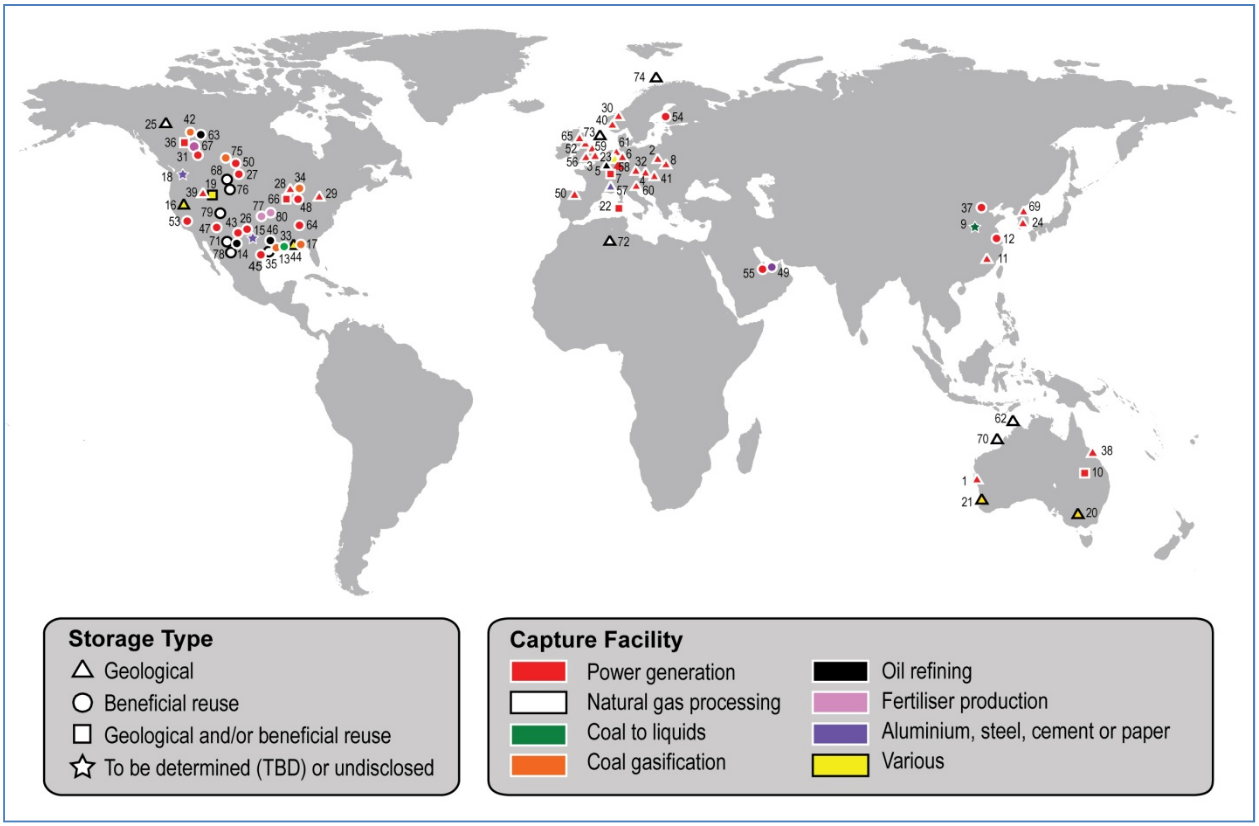


Figure 12A. Active or Planned Large-scale Integrated Projects by Capture Facility, Storage Type and Region (Source: Global CCS Institute 2010)

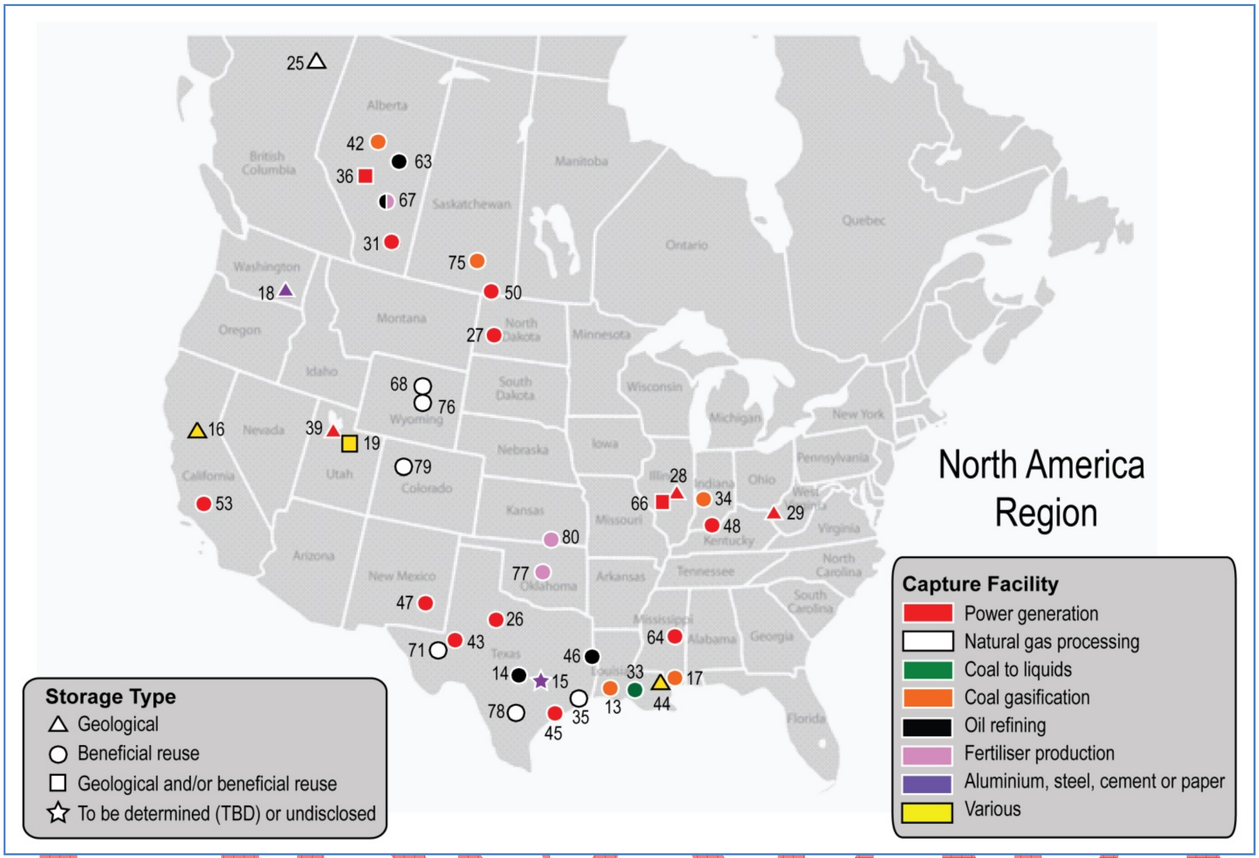


Figure 12B. Active or Planned Large-scale Integrated Projects in North America by Capture Facility and Storage Type (Source: Global CCS Institute 2010)

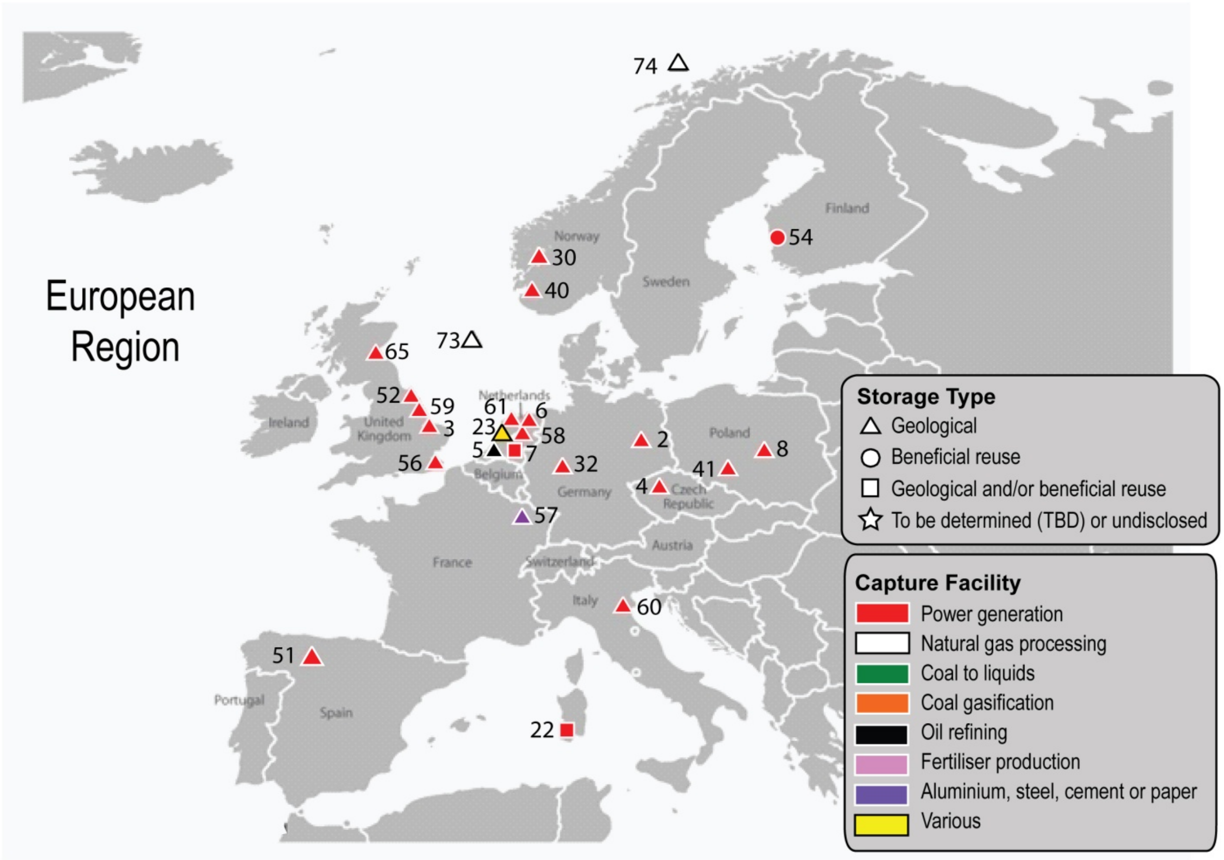


Figure 12C. Active or Planned Large-scale Integrated Projects in Europe by Capture Facility and Storage Type (Source: Global CCS Institute 2010)

2.2. CSLF Activities and Achievements

The CSLF 2004 TRM identified six key activities which were carried out in the period 2004 to 2008 to address cost reductions, secure reservoirs, and development of monitoring and verification technologies. (Figure 13).

TOPIC/TIMESCALE	2004–2008	2009–2013	2014 +
Lower Costs	• Identify most promising pathways • Set ultimate cost goals	• Initiate pilot or demonstration projects for promising pathways	• Achieve cost goals of reduced CCS setup and operations combined with increases in process/electricity generation efficiencies
Secure Reservoirs	• Initiate field experiments • Identify most promising reservoir types	• Develop reservoir selection criteria • Estimate worldwide reservoir "reserves"	• Large-scale implementation
Monitoring and Verification Technologies	• Identify needs • Assess potential options	• Field tests	• Commercially available technologies

Figure 13. 2004 CSLF TRM

Recently completed and ongoing CSLF activities include:

- The development of CO_2 storage capacity estimations (Phase I, II & III);
- Identification of technology gaps in monitoring and verification of geologic storage;
- Identification of technology gaps in CO_2 capture and transport; and
- Ongoing work to examine risk assessment standards and procedures.

More detailed descriptions of CSLF member program activities can be found on the CSLF website. http://www.cslforum.org/

2.3. CCS Project Activities

There are many notable integrated global projects that are established in CCS. The CSLF has recognized approximately 30 CSLF projects, details of which are available on CSLF website www.cslf.org Additional projects and details are available on IEA GHC and GCCSI website.

2.3.1 Operational Commercial-scale Projects

Across the world there are nine operational commercial-scale integrated CCS projects, all motivated by, or linked, to oil and gas production. Four of these projects have a MMV system specifically designed to ensure the permanent storage of CO_2:

1. **Sleipner CO_2 Injection** – North Sea, Norway. This project owned by Statoil captures about 1 million tonnes per year (mtpa) of CO_2 during natural gas extraction, and immediately reinjects it 1,000m below the sea floor into the Utsira saline formation. In

operation since 1996. Shutdown planned in 2019. http://www.statoil.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx

2. **In Salah CO_2 Injection Project** – Ouargla, Algeria. BP runs this project in partnership with Statoil and Sonatrach. Approximately 1.2mtpa of CO_2 captured during natural gas extraction is injected into the Krechba formation at a depth of 1,800m. In operation since 2004. Shutdown planned in 2044. http://www.statoil.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx
3. **Snøhvit CO_2 Injection** – North Sea, Norway. This LNG plant is owned by StatoilHydro and captures 7mtpa of CO_2 that is transported via a 160km pipeline for injection into the Tubåen sandstone formation 2,600m under the seabed. In operation since 2007. Shutdown planned in 2035. http://www.statoil.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx
4. **Weyburn Operations** – Saskatchewan, Canada. This project owned by EnCana and Apache captures about 3mtpa of CO_2 from the Great Plains Synfuels Plant (coal gasification) in North Dakota, USA, transports this by pipeline 330 km across the Canadian border and injects it into depleting oil fields where it is used for EOR. Since injection commenced in 2000 to end of 2009 about 17Mt CO_2 have been stored in these fields. Numerous research activities including baseline and monitoring surveys are associated with the commercial projects. In operation since 2000. http://www.netl.doe.gov/publications/factsheets/project/Proj282.pdf

2.3.2 Operational Demonstration and Pilot Projects

A number of demonstration and pilot integrated projects are in operation, some of them focusing on demonstrating a specific technology or advancing a key component of the CCS chain:

5. **Microalgae Bio-Energy and Carbon Sequestration Project** – Dalate, Inner Mongolia. This project will use microalgae to absorb CO_2 emitted from the flue gas of a coal-derived methanol and coal derived dimethylether production equipment and produce bio-diesel as well as feeds. The absorption capacity will be 320,000 tons of CO_2 annually. The project began in May 2010 and will be completed in 2011.
6. **CO_2 capture and EOR Pilot China SINOPEC Shengli Oil Field** – Shengli Oil Field. This pilot scale test aims to capture CO_2 from flue gas and inject the CO_2 into an oil reservoir for EOR. The project is being extended to use purified CO_2 with 99.5 percent purity for EOR and storage in low-permeability reservoirs. Operation will begin in July 2010.
7. **Huaneng Shanghai Shidongkou Power Plant CO_2 Capture Project** – Baoshan district, Shanghai. This demonstration project is the largest coal-fired power plant post-combustion capture unit in the world. More than 100,000 tpa of CO_2 have been captured, with a purity of more than 99.5 percent that meets the food-grade CO_2 product regulations for beverage usage after a refining system processes the captured CO_2. Operational since 2009.

8. **CO_2SINK/ Ketzin CO_2 Storage Pilot** – near Berlin, Germany. This project operated by GeoForschungs Zentrum Potsdam includes two observation wells and a series of different technologies that allow on-land testing of monitoring techniques without disturbing industrial activities and at lower costs than off-shore or in a desert. Present plans allow 20,000 t CO_2/year to be injected. Injection started in June 2008.
   http://www.co2sink.org/
9. **Vattenfall's Oxyfuel Pilot Plant Schwarze Pumpe** – Brandenburg, Germany. Based on an oxy-combustion concept, 100,000 tonnes of CO_2 per annum are captured from the flue gas after deSOx and deNOx processes and is planned to be transported over 350 km by trucks to Altmark, a depleted gas field operated by GDF Suez. Operational since September 2008.
   http://www.vattenfall.com/en/ccs/schwarze-pumpe_73203.htm
10. **AEP Mountaineer** – Mountaineer Station, New Haven, West Virginia, USA. AEP's Mountaineer plant is a 1,300MW coal-fired power station that was retrofitted with Alstom's patented chilled ammonia CO_2 capture technology on a 20 MWe slipstream of the plant's exhaust flue gas. Once at full scale, this project will capture up to 1.5mtpa of CO_2 that will be compressed using new shockwave technology compression systems and transported via pipeline to multiple saline aquifer storage sites within an estimated 12 miles of the power station. Pilot project is operational since September (capture) and October (storage) 2009 and is scheduled to end in Q3 or Q4 2010. Full-scale operation is expected by 2015.
    http://sequestration.mit.edu/tools/projects/aep_alstom_mountaineer.html
11. **Total Lacq Pilot Project** – Pyrénées-Atlantique, France. This 30 MW_{th} gas boiler project uses oxy-combustion capture technology. CO_2 is transported via an existing 30km pipeline and stored in a very deep (4,500 m) depleted gas field. This project will capture and store 150,000 tonnes of CO_2 over the 2-year test period. Operational since January 2010.
    http://www.total.com/en/special-reports/carbon-dioxide-capture-and-geological-storage/lacq-project-940768.html

2.3.3 Advanced Integrated CCS Projects

A number of commercial-scale and demonstration integrated CCS projects are being developed worldwide. The most advanced of them, i.e. the ones that could be operational by 2015, are listed below. It is however likely that a significant portion of these projects will ultimately be delayed or cancelled, potentially due to a lack of government funding, inadequate regulatory environment, community opposition or changed economics etc. Several projects listed in the 2009 TRM were cancelled, and a majority of them reconsidered their initial schedule.

12. **Callide Oxyfuel Project (Callide 'A')** – Queensland, Australia. This demonstration project will capture up to 10,000 tpa of CO_2 at a 30 MWe power station. The CO_2 will be transported by truck and injected into an on-shore saline formation. This project is being developed through an Australia-Japan technology alliance. Construction has started for this project that is expected to be operational by mid-2011.
    http://www.callideoxyfuel.com/What/CallideOxyfuelProject.aspx

13. **The Collie-Coal-to-Urea-Project** – Collie, Western Australia. This project will produce 2.05 million tonnes of urea per annum using sub bituminous coal as a feedstock. Approximately 2.5 mtpa of sequestration-ready, high purity CO_2 will be generated as part of the urea production process. Project operation is expected in 2013 or 2014. http://www.perdaman.com/our-operations/collie-urea-manufacturing.aspx

14. **Gorgon Project** – Western Australia, Australia. This project developed by Chevron Australia includes the construction of a 15 mtpa LNG plant and a domestic gas plant with the capacity to provide 300 terajoules per day. More than 3 mtpa of CO_2 will be captured and injected near the plant site. Final Investment Decision (FID) for the Gorgon Project was made in September 2009. Operation is expected by 2014. http://www.chevronaustralia.com/ourbusinesses/gorgon.aspx

15. **Wandoan Power IGCC CCS Project** – Queensland, Australia. This project intends to capture up to 2.5 mtpa CO_2 of a 400 MW IGCC plant. The storage component will be conducted through an alliance between Wandoan Power and Xstrata Coal Queensland. Several geological and EOR storage options were identified within the Surat Basin. Operation is scheduled to start in late 2015. http://www.wandoanpower.com.au/

16. **ZeroGen** – Queensland, Australia. This project will use IGCC with pre-combustion capture technology at a 400 MW coal-fired power station and store up to 2 mtpa of CO_2 in deep saline formations in Central Queensland. Demonstration is expected by 2013, with full-scale operation by 2017. http://www.zerogen.com.au/project/overview.aspx

17. **Heartland Area Redwater CO_2 Storage Project (HARP)** – Alberta, Canada. This project will store similar amounts of CO_2 captured at refineries, oil sands upgraders, and chemical plants northeast of Edmonton, Alberta. The selected site has an estimated storage capacity of 1 Gt. Injection is expected to start in 2011 and ramp up to 1 mtpa of CO_2 by 2015. http://www.arc.ab.ca/documents/Reef%20may%20hold%20key%20to%20large-scale%20carbon%20storage.pdf

18. **Project Pioneer** – Alberta, Canada. This project will capture 1 mtpa of CO_2 from one of the three TransAlta's coal-fired power plants in the area, using a chilled-ammonia process developed by Alstom. Project operation is expected to begin in early 2015. http://alberta.ca/home/NewsFrame.cfm?ReleaseID=/acn/200810/24549060A11EE-A487-6EAB-0BA6A4955D18D734.html

19. **Quest CO_2 Capture and Storage Project** – Alberta, Canada. This project will store up to 1.2 mtpa of CO_2 captured at a hydrogen plant at its oil sands upgrader in central Alberta. This project is operated by a joint venture among Shell Canada (60 percent), Chevron Canada (20 percent) and Marathon Oil Sands L.P. (20 percent). Operation is expected to begin in 2015. http://www.shell.ca/quest

20. **Spectra** – Fort Nelson CCS Project – British Columbia, Canada. This project will use CCS at a gas plant after amine separation of the CO_2 from the produced natural gas. CO_2 injection will ramp up to 1.2 to 2 mtpa of CO_2 in a nearby saline formation. Project

operation is expected to begin in October 2010.
http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/19-PCOR_Fort%20Nelson%20Demonstration_PhIII.pdf

21. **GreenGen IGCC Project** –Tianjin, China. This project aims at capturing 2 Mtpa CO_2 from a 400 MW IGCC power plant whose generating efficiency is expected to be 48.4 percent. The CO_2 will be used for EOR in an unspecified location. The project is under construction and is expected to be operational in 2013.
http://www.greengen.com.cn/en/aboutgreengenproject.htm

22. **FINNCAP Meri-Pori CCS Project** – Pori, Finland. This project will retrofit a 565 MWe condensing coal power plant (owned by Fortum and Teollisuuden Voima) with a CO_2 capture facility using an amino-acid post-combustion technology. Maersk Oil (with Maersk Tankers) will operate the shipping transport component of the project. Storage options in depleting oil and gas fields of the Danish North Sea are being investigated. More than 1.2 mtpa of CO_2 will be captured at Meri-Pori. Final Investment Decision is set to be made in 2012 for the project to be operational in 2015.
http://www.finncap.fi/en/

23. **Vattenfall Jänschwalde** – Brandenburg, Germany. A new 250 MW oxyfuel boiler will be built to replace one of the two existing boilers at Jänschwalde power station, while the second boiler will be retrofitted with a post-combustion capture unit. The future storage site has not been firmly chosen yet. In December 2009, Vattenfall was awarded €180 million as part of the European Energy Programme for Recovery (EEPR) for the Jänschwalde demonstration plant.
Construction of the plant is expected to start in 2011. Power station operation is targeted for 2015.
http://www.vattenfall.com/en/ccs/janschwalde.htm

24. **Porto Tolle** – Rovigo, Italy. This project aims at retrofitting one of the three 660 MW units at Enel's Porto Tolle coal power plant with CCS. The capture part will treat flue gases corresponding to 250 MW electrical output. Up to 1mtpa of CO_2 will be stored in an off-shore saline aquifer. The project was awarded €100 million as part of the EEPR. Underground storage is scheduled to start in December 2015.
http://www.enel.com/en-GB/innovation/project_technology/thermal_power_plants/co2_capture/CCS_Project1.aspx?it=-1

25. **Barendrecht Shell** – Rotterdam, The Netherlands. Shell's Pernis refinery produces 1 mt of almost pure CO_2 annually. Two depleted gas fields in nearby Barendrecht will be used to receive the CO_2 captured. Injection is scheduled to start in 2012.

26. **Rotterdam Afvang en Opslag Demo (ROAD)** – Maasvlakte, the Netherlands. E.ON Benelux's power plant at Maasvlakte was retrofitted with a carbon capture pilot plant in 2008. A full-scale CCS project capturing up to 1.1 mtpa of CO_2 is under development as part of the wider Rotterdam Climate Initiative (RCI). In December 2009, the European Commission committed €180 million to ROAD, while the Dutch Government committed a further €150 million in May 2010. Project operation is expected to begin in 2013.
http://www.eon-benelux.com/eonwww/publishing.nsf/Content/Proefinstallatie+voor+afvang+CO2+bij+E.ON+Benelux+op+Maasvlakte_English

27. **SEQ (ZEPP)** – Drachten, The Netherlands. A 50 MWe gas-fired oxyfuel plant and the captured CO_2 will be stored off-shore in a depleted gas field. A 120 MWth Zero-Emission Power Plant (ZEPP) will be built with a view to demonstrate oxyfuel combustion using cryogenic distillation. Progressive scale-up to 1,200 Mwe, capturing up to 1 mtpa of CO_2 will follow. The CO_2 will be used for EGR. http://www.esteem-tool.eu/fileadmin/esteem-tool/docs/ZEPP.pdf
28. **Sargas Husnes Clean Coal Project** – Hordaland, Norway. This project will build a new 400 MW coal-fired power station with post-combustion CO_2 capture. Up to 2.5 mtpa of CO_2 will be transported to an off-shore depleted oil field for EOR. Project operation is expected in early 2015. http://sequestration.mit.edu/tools/projects/sargas_husnes.html
29. **Bełchatów CCS Project** – Bełchatów, central Poland. An existing unit of the Bełchatów power plant will be retrofitted with a 0.1 mtpa pilot carbon capture plant using Alstom's advanced amines technology. A full-scale 1.8 mtpa capture plant will then be installed at an 858 MW lignite-fired unit under construction. Both capture plants will be jointly operated by Alstom and PGE Elektrownia. The project was awarded €180 million as part of the EEPR. Pilot plant operation is expected in 2011. Full-scale CCS plant is targeted for 2015. http://www.alstom.com/pr_corp_v2/2008/corp/53961.EN.php?languageId=EN&dir=/pr_corp_v2/2008/corp/&idRubriqueCourante=23132
30. **CIUDEN's Test Facilities** – Compostilla, Ponferrada, Spain. This project aims at demonstrating the full CCS chain using oxyfuel and fluidised bed technology on a 30 MW pilot plant which will scale up to a 320 MW. Up to 1.1 mtpa of CO_2 will be stored in a saline aquifer. It was awarded €180 million as part of the EEPR. The project is scheduled to be operational at 320 MW by December 2015. http://www.bellona.org/filearchive/fil_CIUDEN_PROJECT_CCS_04A05A09APROT.PDF

31. **Hatfield IGCC/CCS Project** – South Yorkshire, United Kingdom. This capture-only project is developed by Powerfuel Power Ltd and will capture up to 5 mtpa of CO_2 from a 900 MW coal-fired power station. Powerfuel has entered agreements with the UK National Grid to develop the transport component and with other stakeholders for the storage component (North Sea). This project is part of the Yorkshire Forward initiative and was awarded €180 million as part of the EEPR. Project operation is expected to begin in 2014. http://www.powerfuel.plc.uk/id10.html
32. **Masdar CCS Project** – Abu Dhabi, United Arab Emirates. Up to 4.3 Mt/a of CO_2 will be captured from a power plant (1.8 Mt/a), a steel plant (0.8 Mt/a) and an aluminum production facility (1.7 Mt/a), using an amine-based with post-combustion capture technology. The CO_2 will be transported via a 300 km pipeline and used for EOR. Operation is expected by 2013. http://www.bp.com/genericarticle.do?categoryId=9024973&contentId=7046909
33. **Occidental Gas Processing Plant** – Texas, USA. Up to 8.5 Mt/a of CO_2 captured at Sandridge Energy's natural gas processing plant will be transported over a 160-mile pipeline ending at the industry CO_2 hub in Denver City, Texas. The CO_2 will be used for

EOR. The plant is expected to be in service in 2010. This project is currently under construction.

34. **Antelope Valley Station** – North Dakota, USA. The project will use post-combustion capture technology with ammonia on a 120 MW slipstream at a 450 MW coal-fired electricity plant. Up to 1 mtpa of CO_2 will be transported through an existing 330 km CO_2 pipeline and injected for EOR. Commercial operation is expected in early 2015. http://sequestration.mit.edu/tools/projects/antelope_valley.html
35. **Hydrogen Energy California Project (HECA) IGCC** – California, USA. This 250 MW project will use IGCC at a petroleum coke plant to produce hydrogen. The captured CO_2 (2 mtpa) will be stored via EOR. The plant is expected to begin operation in late 2015. http://sequestration.mit.edu/tools/projects/bp_carson.html
36. **MGSC Illinois Basin** – Decatur Project – Illinois, USA. The Midwest Geological Sequestration Consortium (MGSC) partners with Archer Daniels Midland (ADM) in this large-scale demonstration project where ADM's ethanol facility will capture 1 million tonnes of CO_2 over 3 years and store it on site in a saline formation. The project is expected to be operational in early 2011. http://www.netl.doe.gov/publications/press/2009/09008CO2_Injection_Well_Drilling_Begins.html
37. **Northeastern Project** – Oklahoma, USA. This project will capture CO_2 from a 200 MW coal-fired power station fitted onto a 450 MW power station using chilled ammonia post-combustion capture. The CO_2 will be used for EOR. Operation is targeted for 2011. http://www.co2crc.com.au/demo/p_northeast.html
38. **W.A. Parish Plant** – Houston, USA. A 125 MW coal-fired power station will use a post-combustion ammonia-based electrocatalytic oxidation technology to capture 0.5 mtpa of CO_2. The CO_2 will be stored via EOR. The project is expected to be operational by 2013. http://sequestration.mit.edu/tools/projects/wa_parish.html

2.3.3 CO_2 Hubs and Networks

Five major CCS network and hub projects are currently being developed:

39. The **CarbonNet** hub project supported by the State Government of Victoria in Australia, which aims at collecting 3 to 5 mtpa of CO_2 captured in the Latrobe Valley and transporting it via pipeline for sequestration. It is one of the four short-listed projects to be funded under the Australian Government's CCS Flagship Program. http://www.invest.vic.gov.au/200110Victoriaassignscleanenergy29million
40. The **Collie South West Hub Project** supported by the Department of Mines and Petroleum in Western Australia, which aims to store 2.5 to 7.5 mtpa of CO_2 captured from various industrial and power generation sources. The hub concept has been short-listed in the Australian Government's CCS Flagship Program. http://www.perdaman.com/news/2009.aspx
41. The **Alberta Carbon Trunk Line (ACTL)** Project focuses on CO_2 transportation and distribution to EOR projects. The new 240 km pipeline proposed by Enhance Energy will transport approximately 5.5 mtpa of CO_2 captured from different sources in the Heartland

industrial region, with a maximum pipeline capacity of over 14 mtpa (40,000 tpd). http://www.enhanceenergy.com/co2_pipeline/index.html

42. The **Rotterdam CCS Network** in the Netherlands, which is part of the wider Rotterdam Climate Initiative (RCI). This project is to be linked to the CO_2 shipping hub concept being developed by CINTRA in parallel. Several CO_2 emitters in the Rotterdam area are contributing financially to the development of this CCS network concept. http://www.rotterdamclimateinitiative.nl/documents/Documenten/RCI-CCS-ExecSumm.pdf
43. The **Yorkshire and Humber CCS Network**, developed by Yorkshire Forward in the UK. A number of possible models are under technical and financial assessment. http://www.yorkshire-forward.com/sites/default/files/documents/Yorkshire%20%20Humber%20Carbon%20Capture%20%20Storage%20Network.pdf

2.4. Current CCS Pilot-scale Activities

Australia/New Zealand Region

1. **Alcoa Kwinana Carbonation Plant** – WA, Australia. Kwinana Alumina Refinery locks up 70 ktpa of CO_2 from a nearby ammonia plant thanks to a residue carbonation process mixing bauxite residue with CO_2. The refinery was named “Minerals Processing Plant of the Year” in October 2008. Operational since April 2007. Shutdown planned for 2019. http://www.alcoa.com/australia/en/news/releases/20070429_carboncapture.asp
2. **Latrobe Valley PCC project** – Victoria, Australia. A CSIRO mobile pilot PCC facility designed to capture around 1,000 tpa CO_2 was installed at Loy Yang A power station. This project aims at reviewing the technical and economic viability of commercial use of PCC for brown coal power stations, by benchmarking existing and new solvents, obtaining a validated model description of the system and realistic efficiency rates. Operational since May 2008. Shutdown planned for June 2010. http://www.csiro.au/news/CarbonDioxideCapture.html
3. **Munmorah Power Station PCC Pilot Plant Project** – New South Wales, Australia. Based at Delta Electricity's Munmorah black coal power station, this pilot plant aims at assessing and optimising the use of aqueous ammonia for CO_2 capture. Operational since January 2009. https://extra.co2crc.com.au/modules/pts2/download.php?file_id=2059&rec_id=1120
4. **CO_2CRC Otway Project Stage 1 & 2** – Victoria, Australia. CO_2CRC injected 60,000 tons of CO_2 during 2008–2009 from a purpose drilled injection well into a depleted gas field at 2,000 m depth (Stage 1). The project tested modeling prediction, capacity estimation, containment and monitoring technologies (utilizing the original production well) including tracers, seismic and soil, water and air sampling. The project has successfully drilled an additional injection well for residual trapping and saline formation testing and small injection of CO_2 is expected to commence in late 2010 to be followed by larger scale injection in 2011 (Stage 2). Injection for Stage 2 starting in Q2 2010. Monitoring of Stage 1 until 2013 or later. http://www.co2crc.com.au/

5. **CO_2CRC H3 Capture Project** – Victoria, Australia. Three capture technologies are under evaluation at Hazelwood Power Station, with a view to reduce the technical risk and cost of post-combustion capture: solvent, membrane separation and vacuum swing adsorption. Tests have started in Q3 2009. The results will be known in late 2010 or early 2011. http://www.co2crc.com.au/dls/brochures/CO2CRC_H3_brochure_A4.pdf
6. **CO_2CRC Mulgrave HRL** – Victoria Australia. The research program at Mulgrave aims at assessing and optimising pre-combustion capture technologies (solvent absorption, membrane separation and pressure swing adsorption) by evaluating the impact of gas contaminants (H_2S, CH_4, CO) and water; optimising operating parameters; developing engineering solutions; assessing energy integration options; reviewing technical and economic viability for commercial use. Tests started in Q2 2009. The results will be known in late 2010 or early 2011. http://www.co2crc.com.au/research/demo_precombustion.html
7. **Tarong Post-combustion Capture Pilot Project** – Queensland, Australia. Design and construction of a PCC pilot plant at the existing Tarong Power Station, with a view to demonstrate PCC at small scale while testing alternative operating regimes to reduce the energy penalty and additional resource requirements. Operation planned for July 2010. http://www.tarongenergy.com.au
8. **GreenMag-Newcastle Program on CO_2 Sequestration by Mineral Carbonation** – New South Wales, Australia. This project aims at proving the viability of mineral carbonation as a CO_2 sequestration option. It proposes to build and test a pilot scale transformation plant that will produce mineral carbonates to create soil, bricks, pavers and magnesite bricks for use in the agriculture and building industries. Operation expected to start in July 2010. Shutdown planned for January 2015. www.GreenMagGroup.com

India

9. **Demonstration of Capture, Injection and Geologic Sequestration of CO_2 in Basalt Formations of India** – Western India, India. Evaluation of the suitability of a basalt formation in the Deccan Trap for CO_2 storage. The project includes the demonstration of deep bed injection of CO_2 and monitoring of CO_2 movement. Operational since November 2006. Shutdown planned for November 2012. http://www.co2captureandstorage.info/project_specific.php?project_id=157

China

10. **China CO_2 Sequestration and Enhanced Coalbed Methane Recovery Project** – Shizhuang, Qinshui County, Shanxi Province. The objective of the project is to develop systems for CO_2 sequestration and to enhance CBM recovery in unmineable deep coal seams. The project is based on previous cooperative projects between the Chinese and Canadian governments (2002–2007). By May 16, 2010, the project had met its goal of 240 tons CO_2 injection. Operation is ongoing.
11. **Jinlong-CAS' CO_2 Utilization in Chemical Productions** – Taixing, Jiangsu Province. Jiangsu Jinlong-CAS Chemical Co., Ltd. has built a production line to produce 22,000 tons of CO_2-based poly (propylene [ethylene] carbonate) annually. The poly (propylene [ethylene] carbonate) polyol is produced from CO_2 captured from ethanol plants and can

be used to produce highly flame-retardant exterior wall insulation material, leather slurry, biodegradable plastics, etc. Operational, with expansion lines planned through 2016.

12. **Hechuan Shuanghuai Power Plant Carbon Capture** – Hechuan, Chongqing, China. The project plant can annually treat 50 million Nm3 of fuel gases, from which 10,000 tons of CO_2 with the concentration of over 99.5 percent can be captured. The CO_2 capture rate exceeds 95 percent. Operation started in January 2010.
13. **Shenhua Group CCS Demonstration Project** – Erdos, Inner Mongolia. Studies have shown that the underground near the Shenhua direct coal liquefaction plant has a saline aquifer that can be used for CO_2 geological storage with a single well injecting more than 100,000 tons of CO_2 per year. The CO_2 emissions from the Erdos coal gasification hydrogen production center will be captured, purified, and transported to the storage sites by tankers and then injected into the target layer after pressurization. The project is under construction.
14. **CEP CO_2 Capture Ready Gasifier Project** – Lianyungang, Jiangsu, China. This project aims at constructing a demonstration scale, CO_2 capture ready gasifier, and is being developed by the Research Center for Energy and Power (CEP) and the Chinese Academy of Sciences (CAS).

Europe Area

15. **ENEL CCS1 - Post-combustion Pilot Capture Unit** – Brindisi, Italy. Enel plans to build a pilot carbon capture and liquefaction facility on a section of its existing Brindisi plant, with a view to study first and second generation solvent capture. Operation is due to start in June 2010. http://www.enel.com/en/research/carbon/
16. **ZECOMIX** – Rome, Italy. The aim of this capture-only project owned by ENEA is to study and test a zero-emission, high efficiency process producing hydrogen and electricity from coal. It is part of "New technologies and processes for the transition towards hydrogen system," a three- year program sponsored by the Italian government. Operation is due to start in October 2010. http://www.cslforum.org/meetings/berlin2005/index.html

17. **ISOTHERM Pwr ® Flameless Pressurized Oxy-Combustion Technology** – Cerano, Italy. This technology was developed by Enel and Itea and uses high temperatures, oxygen-enriched air and pressurization to produce a flameless oxy-combustion reaction and obtain a CO_2-rich, sequestration-ready flue gas. The technology platform is said to be ready for industrial application. A coal application pilot will be operated, followed by a 250 MW demonstration unit. http://www.iteaspa.it/technologies.asp
18. **P.R.A.T.O. Project** – Sardegna, Italy. The primary objective of this project is to conduct a study for the optimization of a pre-combustion CO_2 capture pilot plant to be integrated to an existing coal gasifier, with a view to significantly reducing capital and operating costs for industrial scale applications.
19. **The Technology Centre Mongstad (TCM)** – Mongstad, Norway. This project is the first step towards full-scale CCS from the CHP plant and the catalytic cracker at the Mongstad refinery (Norway). TCM is currently under construction and plant start-up is expected 2011/2012. TCM DA is owned by the Norwegian State (represented by

Gassnova SF), Statoil, Shell, and Sasol. TCM has an annual capacity for handling up to 100,000 tons of CO_2. The Centre will test CO_2 capture on two types of flue gases using two capture technologies: amine- and chilled ammonia-based. The catalytic cracker flue gas makes testing relevant to CCS on coal-fired power plants. It is possible to add other technologies later on.
http://www.tcmda.no/

20. **Ultra-Low-CO_2-Steel (ULCOS) I** – Norrbotten County, Sweden. This experimental program aims at implementing top gas recycling blast furnace technology in a small pilot plant at Lulea. It is being developed by an ArcelorMittal-led ULCOS consortium. Deliverables include: validation of TGR-BF concept at pilot and demonstration scale; technology testing (oxygen and shaft tuyere, mode of top gas reinjection); demonstration of costs, productivity level and economics of the TGR-BF process; comprehensive set of IP at industrial scale. Operational since January 2004. Next campaign is due to start in Q3–Q4 2010.
    www.ulcos.org

21. **CO_2 Pre-combustion Capture and H_2 Production Pilot Plant Integrated in the Operating IGCC of ELCOGAS Puertollano** – Ciudad Real, Spain. This project aims at demonstrating the technical feasibility of pre-combustion CO_2 capture in IGCC plants, while providing economical data to check commercial viability and optimise integration. ELCOGAS power plant in Puertollano will be retrofitted with a 14 MWt pilot plant capturing 100 tpd of CO_2. Operation is expected in Q2 2010.
    http://www.elcogas.es/

22. **Ferrybridge CCS Trials** – West Yorkshire, United Kingdom. This bench scale project will test carbon capture at Ferrybridge to capture 100 tonnes of CO_2 per day on a 5 MWe slip-stream of the plant. Project operation is expected in early 2011.
    http://sequestration.mit.edu/tools/projects/sse_ferrybridge.html

23. **Undersea Large-scale Saline Sequestration and Enhanced Storage (ULYSSES)** – Kish Bank Basin, off-shore Ireland (near Dublin). Studies undertaken within this project have confirmed a site which may be suitable for off-shore carbon storage capacity in the range of 270 million tonnes.
    http://www.euroinvestor.co.uk/news/story.aspx?id=10986316

Japan

24. **Mikawa PCC Pilot Plant** – Fukuoka Prefecture, Japan. Verification of performance, operability, and maintainability of PCC technology at a pilot plant using actual flue gas of live thermal power plant. Operational since August 2009.
    http://www.toshiba.co.jp/about/press/2008_12/pr0301.htm

25. **Tomakomai CCS Project** – Off-shore Tomakomai, Hokkaido, Japan. This on-going feasibility study aims to use an off-shore aquifer as the storage site for the CO_2 collected at near-by emitters via Extended Reach Drilling wells from the shore. Operation is due to start in November 2010.
    http://ekstranett.innovasjonnorge.no/Felles_fs/CVCTeamNorway/Dokumenter/08%20-%20Ohsumi.pdf

North America

26. **PCOR – Zama Acid Gas EOR, CO_2 Storage, and Monitoring Project** – Northwestern Alberta, Canada. This validation test conducted in the Zama Field is evaluating the potential for geological sequestration of CO_2 as part of a gas stream that also includes high concentrations of H_2S. Results will provide key insights regarding the impact of high concentrations of H_2S (20–40 percent) on sink integrity (seal degradation), MMV, and EOR success within a carbonate reservoir. Operational since October 2005. http://www.netl.doe.gov/events/09conferences/rcsp/pdfs/PCOR%20Zama%20Field%20Validation%20Test%2C%20Keg%20River%20Formation.pdf
27. **PCOR – Bell Creek EOR Project** – Southeastern Montana, MT, USA. The Bell Creek project is premised on advancing the MVA of CO_2 incidentally sequestered at a depleted oil field in the Powder River Basin. The PCOR Partnership will focus on design and implementation of an MVA program, modeling activities, and monetization of carbon credits for the project. Operational since October 2007. Shutdown planned for October 2017. http://www.netl.doe.gov/technologies/carbon_seq/partnerships/development-phase.html
28. **Big Sky Carbon Sequestration Partnership Basalt Field Validation Test** – Washington, USA. The research is one of the first to assess the viability and capacity of deep basalt formations as an option for geologic sequestration. Public outreach is an important component of this project. Shutdown is planned for end of 2010. http://www.netl.doe.gov/technologies/carbon_seq/core_rd/RegionalPartnership/BIGSKY-VP.html
29. **Big Sky Carbon Sequestration Partnership – Wyoming Phase 2 – Riley Ridge Field** – Wyoming, USA. The objective is to perform a field validation test to characterize the Triassic Nugget Sandstone Formation and assess its viability and capacity for a large-scale geologic sequestration test. Operational since September 2008. http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/23a-BigSky_Large%20Volume%20CO2%20Injection%20on%20LaBarge%20Platform_Ph.pdf
30. **SWP – Gordon Creek (SWP Phase III)** – Utah, USA. Objectives of this project include: estimate capacity of the Jurassic Saline reservoirs, estimate seal efficiency, and assess new monitoring methods. Operation is due to start in June 2011. Shutdown expected in 2021. http://www.southwestcarbonpartnership.org
31. **Midwest Regional Carbon Sequestration Partnership – Michigan Basin Geological Test Site** – Michigan, USA. The objective is to test CO_2 sequestration in deep saline reservoirs. Project researchers observed that the behavior of CO_2 in the formation closely matched the behavior predicted by the computer model. The field test data are being used to further calibrate the model. Upon completion of a second injection test, post-injection monitoring will be undertaken and results will be communicated to the public. Operational since September 2006. http://www.netl.doe.gov/technologies/carbon_seq/core_rd/RegionalPartnership/MRCSP-VP.html

32. **PCOR – Beaver Lodge Oil Field Injection** – North Dakota, USA. The project evaluates the potential for geological sequestration of CO_2 in a deep carbonate reservoir for the dual purpose of CO_2 sequestration and EOR. It aims at testing the accuracy with which storage capacity can be predicted, demonstrating MMV technologies and protocols, and providing field validation testing of technologies and infrastructure. http://www.netl.doe.gov/technologies/carbon_seq/partnerships/phase2/phase2_pcor.html
33. **SWP – Jurassic/Triassic Deep Saline Sequestration** – Wyoming, USA. This SWP project is the second stage of a project which involves the injection of 90,000 tonnes of CO_2 into a geologic formation at a depth of more than 2,100m (~7,000 feet), on a large site owned by the Bureau of Land Management. Operational since December 2008. http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/24-SWP_Deep%20Saline%20Sequestration_PhIII.pdf
34. **SWP – Aneth Enhanced Oil Recovery – Sequestration Test G1** – Utah, USA. This project intends to evaluate and maximize efficacy of CO_2 subsurface monitoring technologies and improve ability to track fate of injected CO_2 and calculate ultimate storage capacity. Operational since July 2007. http://www.netl.doe.gov/publications/factsheets/project/Proj443.pdf
35. **SECARB – Black Warrior Basin Coal Seam Project** – Alabama, USA. Objectives for this project are to determine if sequestration of CO_2 in mature coalbed methane reservoirs is a safe and effective method to mitigate GHG emissions; and to determine if sufficient injectivity exists to drive CO_2-enhanced coalbed methane recovery. Operational since September 2009. http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/1-SECARB_Black%20Warrior%20Basin_Coal.pdf
36. **WESTCARB – Validation Phase (Phase 2)** – Various locations, USA. The project's primary goal is to validate the feasibility, safety, and efficacy of carbon storage in two deep saline formations (one in Arizona and one in California) and in forests and rangelands. A secondary goal is to improve the geologic and terrestrial characterization begun during the Characterization Phase (2003–2005) for especially promising storage locations. The West Coast Regional Carbon Sequestration Partnership (WESTCARB) is one of the seven Regional Carbon Sequestration Partnerships. WESTCARB, which is led by the California Energy Commission, includes Alaska, Arizona, California, Nevada, Oregon, Washington, Hawaii, and British Columbia, and comprises more than 80 partner organizations. Project started in 2005 and will end in September 2011. http://www.netl.doe.gov/technologies/carbon_seq/core_rd/RegionalPartnership/WESTCARB-VP.html
37. **Arizona Utilities CO_2 Storage Pilot** – Arizona, USA. This pilot test has three specific objectives: demonstrate the safety and feasibility of CO_2 storage in saline formations in the vast Colorado Plateau region in Arizona; demonstrate and test methods for monitoring CO_2 in consolidated sandstones, shale and carbonate fields; and gain experience with regulatory permitting and public outreach in Arizona. Operational since July 2009. Shutdown in September 2011. http://www.bki.com/westcarb/AZ_pilot.html

2.5. CCS Initiatives

In addition to specific projects, there are agencies and programs designed to develop CCS through coordination, research and demonstration, and deployment efforts worldwide. These include:

2.5.1 International Government and Non-Government Initiatives

1. The **IEA GHG R&D Programme**, which is a major international research collaboration that assesses technologies capable of achieving deep reductions in GHG emissions.
2. The **Intergovernmental Panel on Climate Change (IPCC)**, which provides an objective source of information about climate change initiatives through assessing on a comprehensive, objective, open, and transparent basis the latest scientific, technical, and socio-economic literature produced worldwide.
3. The **Global Carbon Capture and Storage Institute (Global CCS Institute)**, which was established to accelerate the worldwide deployment of CCS technology at commercial scale. The Global CCS Institute was launched in April 2009 by the Australian Prime Minister, and receives up to AU$100 million per year in funding from the Australian Government.
4. The **European Technology Platform (ETP) for Zero-Emissions Fossil Fuel Power Plants (ZEP)** is a joint initiative (public-private partnership) of the European Commission, representing the European Communities and the industry. The main objective of the ETP ZEP is to produce and implement a Strategic Research Agenda (SRA) for CCS deployment in Europe and worldwide.
5. **The Near-Zero Emissions Coal** (NZEC) effort between the UK/EU and China, which aims to construct and operate a 450 MW IGCC power station with pre-combustion capture and storage in a geological formation or through EOR by 2015.
6. The **International Performance Assessment Centre for Geologic Storage of CO_2 (IPAC-CO_2)** with a secretariat in Regina, Canada, and regional networks globally is currently developing standards for geological storage in cooperation with the Canadian Standards Association, as well as developing risk terminology for geological storage. It will provide assurance services to ensure effective risk management for geological storage projects as well as benchmarking of projects and models.
7. **The UK CCS Competition**, which aims to award up to 100 percent funding to a full-scale CCS plant using post-combustion capture and off-shore CO_2 storage. The intention is for the facility to be operational by 2014.

2.5.2 Local, National and Regional Governmental Initiatives and Programs

8. **The U.S. CCS Task Force**, which aims to develop 5 to 10 large-scale demonstration projects on line by 2016. Its primary role is to formally address possible incentives for CCS adoption and any financial, economic, technological, legal, institutional, or other barriers to deployment. It will also outline how to best coordinate existing federal authorities and programs, as well as identify areas where additional federal authority may be necessary.

9. **The Rotterdam Climate Initiative (RCI)** project in the Netherlands, aiming at the development of CCS projects in the Rijnmond region; capture will be at power stations as well as chemical and petrochemical plants, whereas storage will take place off-shore through a newly constructed infrastructure.
10. **The Northern Netherlands CCS Coalition** in the Netherlands, stimulating CCS projects in the northern part of the Netherlands, largely concentrated around the so-called Eemshaven. Projects involved are large-scale power stations and petrochemical plants.
11. **CanmetENERGY Laboratories**, the research arm of Natural Resources Canada, are working on bench and pilot-scale CCS projects in the areas of oxy-fuel combustion, gasification, post-combustion, computational fluid dynamics, and CO_2 compression. These research activities are supported by the state-of-the-art pilot-scale facilities: 0.3 MW_{th} pilot-scale oxy-fuel vertical combustor, entrained flow gasifier (1,500 kPa and 1,650°C) that is capable of operating with dry or slurry feed and $1MW_t$ CFBC pilot-scale facility. CanmetENERGY is also involved in funding and collaborative research in the following areas of CO_2 storage: CO_2 injection; MMV; storage integrity; and capacity estimation. This work will enhance the understanding of how to prevent and mitigate the potential environmental impacts of CO_2 storage.
    http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/clean_fossils_fuels/carbon_capture_storage.html
12. **University of Calgary Field Research and Training Centre** (in association with Carbon Management Canada Inc., see below under R&D Components in CSLF Member Countries). A field test facility is being planned on University of Calgary land near Priddis, Alberta. At the Centre, field-based research on CCS MMV will be undertaken.
13. The **International Test Centre for CO_2 Capture (ITC)** in Regina, Canada, is entering a new phase and will be continuing work on the fundamentals of amine-based CO_2 capture from a variety of flue gas streams. Work includes fundamental research as well as the ability to use 1 tonne and 4 tonne pilot plants, the larger hooked up to both a coal fired electrical station as well as a gas turbine.
    www.co2-research.ca/
14. The **Petroleum Technology Research Centre (PTRC)** at the University of Regina, in cooperation with the Saskatchewan Research Council, continues its work on CO_2-EOR and storage. PTRC manages the IEA GHG R&D Programme Weyburn-Midale CO_2 Storage Project and the Aquistore Project, as well as undertakes extensive research into CO_2-EOR and storage in light, medium, and heavy oils.
    www.ptrc.ca
15. **Oxy-combustion for Coal Fired Power Installations.** This project, that will be followed by a demonstrative program managed by ENEL, focuses on the development and testing of an innovative combustion system fed with coal slurry, operating at 5 bar with exhaust gas recirculation and utilizing the so-called "flameless combustion."
16. **Development of Membranes for the Separation of Hydrogen from Syngas.** The main goal is to develop new membranes by chemical deposition of palladium and its alloys on porous media for use in separating hydrogen from syngas. An especially valuable

application is the Membrane Shift Reactor, already successfully demonstrated at the laboratory scale.

17. **Degradation of a Turbogas Running on Hydrogen Rich Syngas.** Analyses and modeling are carried out concerning the mechanisms that damage the critical materials (due to heat) in aggressive environments from the thermal, chemical, and erosion points of view.
18. **Sorbent Solids Suitable for the Capture from Combustion Fumes.** A capture system just upstream of the chimneys of existing installations is being studied. This can be put into practice using absorption processes in amine solutions.
19. **Innovative Technologies for the Improvement of the Environmental Performance of Powdered Coal Power Plants.** The activity of this research program consists of two strains: a) the development of advanced diagnostic techniques for the monitoring of the pollutants typically associated with coal combustion and for studying the impact of the coal type utilized; b) the development and/or implementation of technologies for the reduction of the pollutant load upstream and downstream of the combustion system, including: the characterization of the process of de-volatilization and combustion of the particles as a function of the characteristic of the coal, the pre-treatment of the coal powder and the treatment of flue streams for the reduction of pollutants.
20. **MILD Combustion Project.** The main goal is to develop and test MILD combustion in different industrial sectors, because of its higher efficiency, strong reduction of NO_x and particulate emission. An experimental program on a 6 MWt pilot installation coal oxyfiring with CO_2 capture is ongoing.

2.6. R&D Components in CSLF Member Countries

Australia

CCS activities in Australia currently include pilot, demonstration, and commercial scale projects at various stages of implementation; finalisation of legislation and regulations for CO_2 storage; and various state, federal and international programmes and funds to accelerate CCS deployment.

The Australian federal government, as well as the state governments of Queensland, Victoria, and Western Australia, have passed legislation and regulations enabling the geological storage of CO_2 both off-shore and on-shore Australia. However, the legislation for the Carbon Pollution Reduction Scheme (CPRS) was rejected by the Parliament and finally postponed by the Australian government after the current commitment period of the Kyoto Protocol which ends in 2012.

Australian federal and state government commitments to CCS include:

- AU$400 million over four years from 2008–2009 committed to the Global Carbon Capture and Storage Institute (Global CCS Institute). The Global CCS Institute was launched in April 2009 to accelerate the deployment of commercial scale CCS projects worldwide;
- Approximately AU$110 million in funding allocated to CO_2CRC to support its activities through 2015. CO_2CRCLtd develops and manages a collaboration between industry, government and university partners and is one of the world's leading collaborative research institutions specializing in CCS. Beginning work as the APCRC in 1998,

CO_2CRC has undertaken Australia's only operational storage project. It also has both pre- and post-combustion capture projects under way;

- Legislation;
- Release of off-shore areas for GHG storage. In March 2009, the federal government released the first 10 off-shore areas ever offered for commercial geological GHG storage; AU$2.4 billion announced in the 2009–2010 federal budget for low emissions coal technologies including new funding of AU$2 billion for industrial-scale CCS projects under the Carbon Capture and Storage Flagships programme;
- AU$600 million committed or allocated to date for CCS pilot and demonstration projects around Australia from the Low Emission Technology Demonstration Fund and National Low Emission Coal Initiative programs. Many of these projects also share in greater than A$400 million of state government funding and other industry funding;
- Around AU$1 billion from state governments to low emissions technology and climate change funds and other state-based programs; and
- AU$165 million of federal support for programmes including the National Carbon Mapping & Infrastructure Plan, National Coal Research Program, Carbon Storage Initiative and other studies, plus funding for international partnership programmes such as the Asia Pacific Partnership on Clean Development and Climate.

Canada

In the last two years, Canada's federal and provincial governments have committed more than CAD 3 billion in funding for CCS. These investments support several interdependent initiatives focusing on reducing market barriers and realizing the full potential of CCS. Key categories of action include: supporting innovation through development and demonstration of new technologies; accelerating deployment by establishing industry standards and reducing investment risks, building deployment capacity, and establishing and strengthening regulation; and facilitating information sharing by sharing best practices and knowledge and enhancing public awareness and acceptance.

The Alberta Government is developing procedures and protocols for data, information, and knowledge sharing for the four CCS projects in Alberta that have received provincial funding to the tune of CAD 2 billion in total (see projects #4, 5, 6, and 7 in Section 2.3).

Carbon Management Canada Inc. http://www.carbonmanagement.ca/home.html is a national not-for-profit research network involving over 20 Canadian universities hosted at University of Calgary that was created in December 2009 with federal, provincial, and industry funding. Research is focused on four major objectives: a) create carbon-efficient recovery and processing (CERP) technologies; b) innovate to reduce the cost of carbon capture and storage (CCS); c) design protocols and tools for safe, secure, verifiable carbon storage; and d) analyze the risk, business, and regulatory options to inform policy and investment, engage the public, and develop the supportive framework necessary to deploy publicly acceptable technologies at appropriate scale.

The Research Chair on Geologic Sequestration of CO_2 in Québec, Canada, aims at evaluating the CO_2 storage capacity in the province of Québec, characterizing potential storage sites in deep saline aquifers and testing one of these sites. This research chair is financed by the Provincial Government of Québec http://www.chaireco2.ete.inrs.ca/ at the Institut National de la Recherche Scientifique (INRS).

CCS Nova Scotia is currently directing studies for the economic and technical feasibility for CCS both on-shore and off-shore in Nova Scotia. Studies on capture technology options and the development of on-shore legal and regulatory roadmaps for the province will be awarded in the summer of 2010, with other activities to follow.

Canada, the United States, and Mexico are collaborating to develop an atlas of major CO_2 sources, potential CO_2 storage reservoirs and storage estimates in the three countries, based on common methodologies for estimating reservoir capacities, common data gathering and sharing protocols and a uniform geographical information system. The atlas will be used to develop a comprehensive understanding of the potential for CCS in North America and will be particularly relevant for cross-border basins, where it will eliminate international "fault lines" and ensure compatible estimates of sink capacities. The first version of this atlas is scheduled to be released in the spring of 2012.

Denmark

A study for planning a pilot project for CO_2 EOR in a Danish oilfield has been initiated. The project is supported by the Danish High-Technology Foundation, and led by DONG Energy. Studies on modeling of oxy-fuel combustion are ongoing at Aalborg University and the Technical University of Denmark.

The Geological Survey of Denmark and Greenland GEUS are involved in several international projects on CCS. http://www.geus.dk/co2 In the CESAR project, the pilot CO_2 capture plant (established as part of the CASTOR project) at the Danish power station Esbjergværket will be used to test more effective solvents.

Denmark supports the IEA GHG R&D programme, and thus supports the CCS activities in this programme.

European Union

The 7th Framework Programme (FP7) is the main instrument at the disposal of the European Commission to support research, technology development, and demonstration in strategically important areas. Clean coal technologies and CCS are top priorities in FP7. The main objectives are increasing the efficiency of fossil fuel-fired power plants, decreasing the cost of CO_2 capture and storage, as well as proving the long-term stability, safety, and reliability of CO_2 storage. For the near future, the CCS Work Programme foresees in particular the research needed in support of large-scale demonstration programmes in the domain of CCS.

In the revised Emission Trading System (EU ETS) directive, adopted by Parliament and Council in December 2008, 300 million allowances have been reserved, until 2015, for the support of large-scale demonstration projects in the areas of CCS and innovative renewables. These will support industrial scale energy demonstration projects, costing hundreds of millions of Euros per project.

In addition to this, the "recovery package" approved by the Commission in July 2009 grants €1.5 billion to support 15 CCS and off-shore wind demonstration projects in 7 Member States. The 6 selected CCS projects are: Jänschwalde (maximum contribution of €180million), Porto Tolle (€100million), Rotterdam (€ 180million), Bełchatów (€180million), Compostilla (€180million), and Hatfield (€180million).

The European Union CCS Directive 2009/31/EC on geological storage of CO_2 was approved in April 2009. EU Members are required to transpose this directive into national legislation by 2011. Importantly, the Directive requires that all storage sites be assessed following the EIA Directive. A complementary, comprehensive set of guidelines is scheduled to be published in October 2010. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

France

The ANR "CO_2 Program" (National Research Agency) aims to improve production processes to generate nearly pure flows of CO_2 at lower cost and to devise methods for the storage of CO_2, particularly in deep geological formations. http://www.agence-nationale-recherche.fr/EDEUK

From 2005 to 2008, ANR supported 33 CCS projects for a total amount of €27 million. The call for projects is open to public-private partnerships on five thematic areas:

- Capture and transportation;
- Storage and MMV;
- Risk assessment, safety criteria, regulations;
- Breakthrough technologies for CO_2 capture; and
- Social, economical, and environmental evaluations.

The French Environment and Energy Management Agency (ADEME) supports initiatives concerning CO_2 capture and storage and devotes special attention to energy efficiency, socio-economic issues, and environmental impacts. Since 2002, ADEME invested more than €5 million to support R&D projects. The conclusions of the "Grenelle de l'Environnement" in December 2007 led to a proposal to create dedicated "demo funds" of €100 million on CCS projects, managed by ADEME. This research aims to validate technologies that are still in their development stage. The priority research areas relate to capture by post-combustion or oxyfuel combustion, the demonstration of a localised transport infrastructure, and storage in deep saline formations. The research will support demonstration plants that are one-tenth the size of full scale industrial plants for two to three years. http://www.dr6.cnrs.fr/SPV/spip.php?article73

In December 2009, France's plan for a carbon tax was abandoned after its constitutional court ruled the tax would violate principles of equality because of the high number of discounts or exemptions that were announced for industry and agriculture. A revised measure is set to be introduced later in 2010.

Germany

The CO_2-Reduction-Technologies (COORETEC) programme of the Federal Ministry of Economics and Technology is part of the energy research programme of the federal government. The principal goal is the development of technologies to mitigate CO_2-emissions from power plants based on fossil fuels. Besides efforts to increase the efficiency of these power plants, the CO_2 capture is a major topic. CCS projects are oriented towards a large scale demonstration in 2014/15 and the availability of the technology in 2020. Collaborative research projects between science and industry are in the focus of the COORETEC programme. In the period 2004–2008, nearly 240 projects, with an amount of more than €124 million project funding, have been approved.

The GEOTECHNOLOGIEN-Programme (CO_2-Storage) of the Federal Ministry of Education and Research targets R&D-funding on basic research as well as on large field experiments focused on CO_2-storage. Objectives are the development of technologies that enable safe and permanent storage as well as long-term and reliable monitoring. Furthermore, projects are oriented towards a large-scale demonstration. Collaborative research projects between science and industry comprise the focus of the GEOTECHNOLOGIEN-Programme. For the period 2005–2011, 24 projects, with an amount of more than €50 million project funding, have been approved.

A draft bill designed to provide a framework for the development of pilot CCS projects in Germany was written through a partnership between the German Minister for Economy and Minister for Environment and submitted in July 2010. Pilot CCS projects will need to apply for approval by the end 2015 and will not be able to store more than 3 mtpa of CO_2 each, while the country's overall injection rate of CO_2 will be capped at 8 mtpa. This framework will be reviewed and adjusted in 2017.

Greece

The Centre for Research and Technology Hellas/Institute for Solid Fuels Technology and Application (CERTH/ISFTA) is the main Greek R&D institution participating in a number of CCS projects of the EU Framework Programmes, including GESTCO, ENCAP, CASTOR, GeoCapacity, CACHET, FENCO-ERA.NET etc as well as national CCS R&D projects funded by the Greek Operational Programme "Competitiveness" (2000–2006). In addition, CERTH/ISFTA is currently involved in the FP7 project "Research into Impacts and Safety in CO_2 Storage" (RISCS), which aims to provide research on environmental impacts to underpin frameworks for the safe management of CO_2 storage sites.

The CO_2 storage capacity of the Greek hydrocarbon fields and deep saline aquifers has been estimated under the EU GeoCapacity project providing opportunities for CCS implementation. Within the framework of a contract with Public Power Corporation S.A. (PPC) CERTH/ISFTA has completed a techno economic study related to the feasibility of a CCS demo project in North Greece. Finally, taking into account the high fossil fuel dependency of the national electricity generation mix CCS related R&D activities are included as a high priority research topic in the Greek National Energy Programme 2007–2013.

CERTH/ISFTA represents the Greek government in international organisations and European Committees, such as in the United Nations, Committee of Energy of European Committee, International Energy Agency, and Carbon Sequestration Leadership Forum, ETP ZEPP, etc.

Japan

R&D activities on CCS started in late 1980s which included various storage options (i.e., ocean storage, Enhanced Coal Bed Methane [ECBM], and geological storage). After the successful geological storage experiment in Nagaoka and preliminary evaluation of storage potential, the priority of R&D has been shifted to "sub-seabed" geological storage. R&D activities — which include various capture options (chemical absorption, membrane, and oxyfuel), monitoring method, long-term simulation and so on — are conducted.

Japan CCS Co., Ltd. http://www.japanccs.com/en_japanccs/index.html, established in May 2008 for the implementing CCS demonstration in Japan, carries out the feasibility study for total CCS systems and is conducting the geological survey at some candidate fields as an inclusive survey for selecting demonstration sites.

Additionally, as a responsible permitting authority under the Marine Pollution Prevention Law, which was amended to include sub-seabed CO_2 storage, the Ministry of Environment has conducted a project to develop the environmental impact assessment and monitoring protocols.

Korea

The Ministry of Education, Science & Technology (MEST) is responsible for administering the 10-year Carbon Dioxide Reduction & Sequestration (CDRS) program established in 2002. www.cdrs.re.kr The third phase of the CDRS program was launched in 2008 with a budget of US$20 million for CCS. The program has mainly focused on developing breakthrough and novel CO_2 capture technologies such as dry sorbent CO_2 capture, ammonia absorption, membranes, and oxyfuel combustion. Dry sorbent CO_2 capture technology for post-combustion developed by KIER and KEPRI has shown excellent performance in 25 kW fluidised bed CO_2 capture process and is currently being scaled up to 0.5 MW, slip-streamed from 500 MW Hadong coal-fired Power Plant.

The Ministry of Knowledge Economy (MKE) through KETEP www.ketep.re.kr has supported several CO_2 capture technologies including post- and pre-combustion and oxy-fuel combustion since 2006. These programs focus on the demonstration of CO_2 capture technology from a few MW to 300 MW until 2017 and are being implemented in cooperation with R&D institutes, the power industry, universities, and heavy industry, led by the Korea Electric Power Research Institute (KEPRI). The 2009–2012 government funding is about US$170 million.

The Ministry of Land, Transport and Maritime Affairs and MKE are also supporting the assessment and examination of the CO_2 geological storage capacity estimation in Korean off-shore and on-shore geological formations.

Mexico

Mexico has started studies to incorporate a post-combustion capture system in a power plant that is currently being redesigned to use coal instead of oil as primary fuel. The power plant (Tuxpan) consists of six 350 MW units and in a first stage capture could be done in one unit, with the possibility of expanding it to two units. The CO_2 will be used by the oil industry for EOR in the nearby fields (100 Km). The preliminary studies are being one by the national utility (CFE) and the Institute of Electrical Research (IIE) with some support from the Center Mario Molina. The power plant, converted to coal, would be operational in the period 2013–2014, with the capture system operational shortly afterwards. Additionally a project to use CO_2 to grow algae to produce ethanol is being developed by the company BIOFIELDS and the CO_2 will be provided by the Puerto Libertad Power Station that is also being converted to use coal.

Netherlands

CAPTECH is a research programme of six Dutch consortium partners. The programme runs from 2006 until 2009 and is coordinated by ECN. The aim of the consortium is the qualification of CO_2 capture technologies with power plant efficiency losses less than 5 percentage points, resulting in capture costs not higher than 20 to 30 €/tonne of CO_2 depending on fuel type. The budget of the programme is €2.5 million per year, and is financially supported by Dutch government (EOS). http://www.co2-captech.nl/

The Carbon Capture, Transport and Storage (CATO) R&D programme is implemented by a strong consortium of Dutch companies, research institutions, universities, and environmental organisations, led by the Utrecht Centre for Energy Research (UCE). Given its size, €25.4

million, the CATO programme can be regarded as the national research programme on CCS in the Netherlands. The Dutch government supports CATO with €12.7 million through the BSIK subsidy programme, managed by SenterNovem. CATO runs from 2004 until the end of 2008. This programme will be followed shortly by a second step in parallel to the CCS pilot en demo plants; foreseen budget is €90 million. http://www.co2-cato.nl/

The first CATO program (CO_2 Afvang, Transport en Opslag) was initiated in 2001 and acquired funding in 2003 (25.4 million, 50 percent of which was funded by the Ministry of Economic Affairs). For CATO (in future CATO-1) its 17 partners the actual work started in 2004. The program continued until the end of 2008; some PhD work ongoing until 2009.

The aim of CATO-1 was to identify whether and how from an economical, technical, social and ecological point of view CCS would contribute to a sustainable energy system in the Netherlands. And under which conditions CCS could be implemented in the Dutch energy system. A prime characteristic of the programme was that all major stakeholders and a number of research groups from very different fields of expertise were working together within an integrated framework. CATO-1 has provided several innovations that have put the Netherlands in a leading position in the international CCS community.

The mid-term external review of CATO-1 took place at the end of August 2007. The international review committee formulated the following conclusions with regard to the follow-up of the program:

“CATO has developed into a successful research network in the Netherlands and has "de facto" become the Dutch national CCS program. It should be noted that this was not the original intention but through the nature of the activity, CATO has initiated numerous CCS projects in the Netherlands that are now highly relevant to the new national Dutch policy on climate change where CCS is recognised as an important element. CATO is therefore a ‘gift to government’ and has established a much needed basis of a national capability in CCS. CATO is well linked to CCS research activities internationally, especially in Europe. It is one of the few national European CCS programs covering the entire CCS chain. The active participation of industry, research institutes universities and NGOs makes CATO a powerful consortium which is similar in nature to the highly influential ZEP EU Technology Platform.”

The CATO-2 program is a demand driven R&D program and focuses on facilitating and enabling integrated development. This means that government and industries set the priorities within the research program: the “problem owners” are leading. The core of the CATO-2 program (ca. 70 percent of the R&D effort) exists of 11 sites, each offering opportunities for applied research on CCS. Combined, they cover the entire CCS chain. The remainder of the resources will be spent on general applied research on cross cutting issues in support of these initiatives and on fundamental (application potential 5 to 10 years) research.

The CATO-2 program will focus a significant part of its applied research efforts on the port of Rotterdam area (off-shore included) and the Northern Netherlands region. This is in line with the Dutch ambition to realise large-scale demonstration sites in these regions. At the same time it will forge a strong link between the CATO-2 program and the regional needs. Additional locations are in Limburg.

CATO-2 research will be performed in five Sub Program lines. Dissemination and international cooperation are listed under program coordination.

The five subprograms are:

- CO_2 Capture;
- Transport and CCS chain integration;
- Subsurface storage of CO_2 and monitoring storage;
- Regulation and safety; and
- Public perception. http://www.co2-cato.nl/

Norway

The Norwegian RD&D program CLIMIT is run in collaboration between state-owned Gassnova SF and the Research Council of Norway. The annual budget from the Norwegian Government is approx. US$15 million for R&D and US$13 million for pilot & demonstration. The program covers the full CCS chain with capture, capture, and storage of CO_2 from fossil-based power production. http://www.climit.no/?language=UK

Recently, two centers for environmentally friendly energy technology within CCS have been established, with annual budgets from the government of US$4.5 million.

Poland

The Polish Clean Technology Program includes CCS as part of the government's energy strategy. A draft new “Geological and Mining Law” is due to be presented in the second or third quarter 2010; the amended version will transpose the EU CCS Directive into national Polish Law. Full legislation related to geological sequestration of CO_2 is scheduled to be implemented in 2011.

A program launched by the Polish Ministry of Environment seeks to identify suitable storage sites, with a budget of EUR€10 million. The Polish Government has also formally endorsed the two CCS demonstration projects being developed at Belchatow and Kedzierzyn.

The Polish Government’s approach to financing promotes international partnership and recommends the intervention of an EU-sponsored fund and/or of the World Bank through a dedicated CCS fund.

Saudi Arabia

Saudi Arabia developed a comprehensive carbon management roadmap with CCS and CO_2 EOR R&D as major components. Other components include technology development of CO_2 capture from fixed and mobile sources, and CO_2 industrial applications. The roadmap seeks to contribute to the global R&D efforts in reducing GHG emissions through the development of technological solutions that lead to sustainable reductions in CO_2 levels in the atmosphere. These R&D activities are pursued through different R&D centres, and universities such as King Abdullah University of Science and Technology (KAUST), and King Abdullah Petroleum Studies and Research Centre (KAPSARC), with Saudi Aramco having a strong leadership role in advancing these technologies.

A pilot CO_2 storage is planned as part of CO_2-EOR demonstration project. In addition, a CO_2 storage atlas will be produced.

South Africa

South Africa is investigating CCS as a GHG emission mitigation measure as a transition measure until renewable and nuclear energies can play a greater part in the South African energy economy. In order to develop capacity, both human and technical, in this relatively new field, a

Centre for Carbon Capture and Storage commenced operations 30 March, 2009 within the South African National Energy Research Institute. The Centre was officially launched during a CCS Week held during September/October, 2009. The Centre is a private/ international/ public partnership and financed from local industry, SANERI, government, and international sources.

The vision of the Centre is that a carbon capture and storage demonstration plant will be operational in South Africa by the year 2020, which requires development of in country human and technical capacity.

A carbon geological storage Atlas was scheduled to be launched 24 August 10 — but has been postponed as the Minister is in China on that date — a new date is yet to be advised. A test injection, as a proof of concept to show that CO_2 can be safely geologically stored in South Africa, is scheduled for 2016.

United States

The U.S. Department of Energy's Fossil Energy Program is working to ensure that cost-effective, near-zero-emission coal power plants equipped with CCS will be available to meet world energy demand in the future. The U.S. program has appropriated US$692 million and US$404 million in FY2009 and FY2010, respectively, to support the development and demonstration of innovative technologies critical to coal systems with CCS including pre- and post-combustion capture processes; advanced gasification systems; hydrogen turbines; fuel cells; high strength materials and sensors; CO_2 capture and compression technologies; and others.

More mature CCS technologies are demonstrated at commercial scale through DOE's Large-Scale Demonstration programs. DOE's seven Regional Carbon Sequestration Partnerships (RCSPs) are each conducting large-scale CO_2 injection tests (up to 1 million tons per year), to validate the potential for safe and permanent geologic storage, and are addressing regional, state and local regulatory, realty and public participation issues. In addition, the American Reinvestment and Recovery Act (ARRA) of 2009 provides an additional US$3.4 billion for CCS activities. http://www.fe.doe.gov

To this date, 20 U.S. states have passed legislation specifically dedicated to CCS: California, Colorado, Illinois, Indiana, Kansas, Kentucky, Louisiana, Massachusetts, Minnesota, Montana, New Mexico, North Dakota, Oklahoma, Pennsylvania, South Dakota, Texas, Utah, Washington, West Virginia and Wyoming. Illinois and Texas are the two states with the most advanced CCS-related legislation. http://www.ucl.ac.uk/cclp/ccsdedlegnat-US-State.php?status=I

MODULE 3: GAP IDENTIFICATION

At their 2008, 2009, and 2010 meetings, the G8 leaders reinforced their commitment from the Gleneagles meeting in July 2005 to accelerate the development and commercialisation of CCS by strongly supporting:

- The recommendation of International Energy Agency (IEA) and the CSLF to launch 20 large-scale CCS demonstration projects by 2010; and
- The broad deployment of CCS by 2020, as one of several measures to mitigate climate change impact.

Similar targets have been adopted by the ZEP and followed up by several governments. Achievement of this target in the near future is strongly dependent on the funding available. IEA and CSLF, in cooperation with the Global CCS Institute (GCCSI) have recently issued a report on the progress of work towards these targets and the recommendations for the next steps towards meeting them (IEA/CSLF, 2010). According to this report, “CCS has advanced towards commercialisation, notably through the commissioning of CCS pilot plants, continued learning from plants already in operation and the development of legal and regulatory frameworks.”

Several governments have committed to provide over US$ 26 billion in funding support for demonstration projects: the United States, Canada, Norway, the Republic of Korea, Japan, the United Kingdom and Australia in addition to the European Commission. The government commitments will facilitate the launch of between 19 and 43 large-scale CCS integrated demonstration projects by 2020 (IEA/CSLF, 2010). http://www.globalccsinstitute.com/downloads/general/2010/The-Status-of-CCS-Projects-Interim-Report-2010.pdf Four large-scale CCS projects will be in operation including: In Salah in Algeria, Sleipner and Snøhvit in Norway, and Weyburn-Midale in Canada. For one commercial-scale project (in Gorgon in Australia), contracts are under development and ensure that the target is reached.

CCS RD&D activities must be conducted in parallel to ensure broad CCS deployment within the desired time frame. These are quite different technology development phases. The initial demonstration projects will have to be based on currently available technologies, and operators, engineers, and researchers will learn how to progressively improve those technologies through experience. This learning-by-doing phase is quite distinct from basic R&D in pursuit of the technology breakthroughs likely to be required for major longer term cost reductions as a basis for generally affordable deployment. R&D projects will involve basic research with the objective to develop safe and cost-effective processes for the capture, transport, and long-term storage of CO_2.

This Module 3 identifies technology gaps for each of the three main components in the CCS chain and lists several actions that would be required to close the gaps. Some factors occur both in the general discussion of R&D gaps and the need for demonstration projects and under tasks and priorities for each technology. This is deliberately done in order to emphasize their importance.

Recognizing that CO_2 capture and compression equipment significantly reduces the available electrical energy output, there is a need to improve overall power station efficiency. This is to reduce as far as possible the impacts of the additional plant loads due to capture technologies. Efficiency initiatives include development of high efficiency gas turbines and new cycle concepts as well as development of alternative power generation processes that have the potential to give improved economics when paired with absorption capture. Other major CO_2 emitters where CCS is applicable include gas treatment, refineries, iron and steel and cement production, and their efficiency in the context of CCS need similar consideration. However, improvements in the energy efficiency of the base technologies is outside the scope of this TRM.

Key changes and progress from the 2009 TRM

This section is intended to briefly review progress and changes from the 2009 version of the CSLF TRM, identifying both the major gaps that have been addressed and new areas of focus. As stated in Module 0, there has been significant international activity in the field of CCS since the 2009 version of the CSLF TRM. Of particular interest to this update are the TRM issued by the International Energy Agency (IEA) (IEA, 2009) and the recommendations of European Technology Platform for Zero-Emission Fossil Fuel Power Plants (ZEP) for research to support the deployment of CCS in Europe beyond 2020 (ZEP 2010). The IEA TRM (2009) covers all aspects of CCS whereas this 2010 update of the CSLF TRM and the ZEP (2010) document focus on technology aspects. Thus, the three documents will serve to supplement and complement each other.

Capture. Progress has been made in advancing breakthrough carbon capture technologies such as membranes, but these technologies are still in their infancy. A number of laboratory and pilot projects have been launched globally that focus on reducing energy requirements and improving the purity of the CO_2 stream. However, it may take a few years before the full conclusions of these projects are known and shared with the wider community.

Transportation and Infrastructure. The evolution of R&D in this area has resulted in the identification of more gaps, albeit more specific in nature. This is a consequence of developing a greater understanding of the technical and economic aspects of CO_2 transport. Previous gaps are retained, and, in numerous cases, expanded. Safety practices and an understanding of risks associated with transport of the compressed gas is still a major focus, but with greater emphasis on the effect of impurities in the gas stream. Another area of interest addresses the impacts and consequences of pipeline transportation of CO_2 over the long term and the effects on the pipeline system.

Studies such as the Australian Carbon Storage Infrastructure Plan (Spence, 2009) http://www.ret.gov.au/resources/Documents/Programs/CS%20Taskforce.pdf have begun to identify the tasks, resources and infrastructure required for regional-scale deployment of CCS. In the case of the Australian study a key finding was that several years, and expenditures in the order of 100 million dollars, may be required to acquire and analyse the storage exploration and characterisation data needed to provide sufficient storage assurance to underpin the development of multi-billion dollar projects.

Storage. The critical knowledge and information gap for advancing storage projects and technology is around data. Site scale and site specific data are required to underpin the development of demonstration project, and operational data from these projects are needed to refine and develop our knowledge of storage issues. Site scale and operational data are also required to increase government, industry and public understanding of, and confidence in, storage projects. Furthermore, although a global storage atlas has not been attempted, our understanding of regional capacity and potential for geological storage has improved with the completion or undertaking of several national and regional storage atlases. In addition to the need for general models and storage guidelines, there is now a shift in emphasis towards specific storage issues such as capacity estimation, well design, well integrity, and prevention of well leakage. Major progress towards a consistent methodology for capacity estimation in deep saline reservoir storage systems has been made but this area still remains a key priority. The effect of pressure build-up within a reservoir or deep saline aquifer, as well as water management, have emerged as key issues where improved knowledge is needed. Once again, these issues have come out as our understanding of the effects of CO_2 on geological systems has improved. The general understanding of deep saline aquifers including reservoir and cap rock characterisation, injectivity, modeling, and verification has increased over the last years, but gaps remain. Knowledge gaps regarding depleted oil and gas fields, coal seams, and mineral storage have remained unchanged, and include a general need for site specific selection, assessment, and an understanding of the nature of the various sites. Similarly, CO_2 storage in other geological media such as basalts and shales still requires research and better understanding. Lately, with the advent of oil and gas production from shales using horizontal wells and fracturing technologies, new challenges arise regarding cap rock integrity.

Michael et al. (2009) provided a summary of experience from existing storage operations, commercial scale, as well as pilot scale. They state that pilot projects generally have comprehensive monitoring but comprise only small volumes, whereas some of the commercial-scale projects are in an opposite situation, and that some of the commercial projects have “unrepresentatively good” reservoir properties. They point to remaining issues such as need to “prove” that migration outside the reservoir can be detected and that there is a need for a more comprehensive portfolio of aquifer storage projects and monitoring strategies.

Although significant knowledge gaps have been identified, research carried out within CCS in the last decade has made it possible to issue guidelines or Best Practices documents. In Norway, three industry consortia led by Det Norske Veritas (DNV, 2009, 2010a, 2010b) issued guidelines on capture, pipeline transport, and storage. The CO_2 Capture Project (CCP 2009) has issued a technical basis for CO_2 storage, based on project research results and company experiences. The World Resources Institute has also issued CCS guidelines (WRI, 2008).

This 2010 version of the CSLF TRM discusses the gaps identified above in more detail. The main changes from the 2009 CSLF TRM are:

- Stronger emphasis on CCS integration and demonstration of complete CCS value chains including CO_2 source and capture, transport, and storage of CO_2;
- Stronger differentiation between demonstration and R&D; and
- Expanded and more detailed milestones for capture.

3.1. The Need for New/Improved Technology

Much of the current implementation of CCS has occurred in the natural gas industry where separation of CO_2 from the gas stream is required for commercial and safety reasons and the incremental cost of capture and storage is relatively small. Wider implementation into power generation and other industries will require appropriate actions and drivers to reduce cost such as:

- Implementation of commercial scale demonstration projects;
- Further research to achieve cost reductions and safe long-term storage of CO_2, including major data acquisition programmes for site characterization and selection;

- Emission regulations or incentives to limit the discharge of CO_2 to the atmosphere; and
- Appropriate financial incentives to reduce the financial burden of CO_2 capture and storage.

This TRM deals only with the first two bullet points.

Currently, insufficient information exists on the design, cost, and space requirements, operation, and integration of CCS with plant facilities, mostly in, but not limited to the power generation sector. This lack of information impedes making power stations and industrial plants CCS-ready for when CCS technology achieves commercial status. In addition to gaining the needed experience and information from implementing demonstration projects, it is crucial that pertinent available information be made available to the world community and that needed follow-up R&D stemming from the demonstration projects be identified and undertaken. The methods to ensure knowledge transfers include:

- Conduct periodic technical reviews of all aspects of recognized large-scale CCS demonstration projects and report on the “lessons learned”; and
- On a periodic basis, update the TRM to assess progress in covering knowledge and technology gaps and include technology gaps identified during the technical assessment of demonstration projects.

3.2. Commercial-scale Demonstration Projects

It is necessary to demonstrate CO_2 capture and storage in several large-scale projects in order to improve the technical and commercial viability of CCS and to optimize the technology and reduce costs. Large demonstration projects will help establish expertise and industrial capability for the manufacture and installation of the plants, and also in site selection, characterization, and monitoring. In addition to giving the necessary operational experience, this will contribute to lower costs, build public confidence, and ensure CCS is commercialized by 2020. Importantly, it will spur action in all countries. As a global solution to combating climate change, CCS could also boost the industrial activity, create new jobs, and promote technology leadership. The IEA TRM (IEA, 2009) discusses these aspects in more detail.

CO_2 capture in early commercial scale demonstration plants may be based on existing technologies that have not yet been deployed at the scale needed (e.g., gas or coal fired 500 MW power plants), nor used yet as part of a fully integrated CCS chain. Thus, there is a need to scale-up and integrate capture technologies for commercial-scale demonstration projects.

The time, cost, and resources required to locate viable storage sites, and to then characterize them to the degree of assurance required for multi-billion investment decisions are often heavily underestimated by the funders, be they governments or other CCS project proponents. Each demonstration project will need detailed mapping and characterization of the receiving reservoir. Furthermore, each project will have to undertake a thorough and time consuming approval process including determining the methodology and cost of suitable monitoring technologies. Consequently, the exploration and characterization studies must start as soon as possible to allow for the necessary lead times.

Efficient transportation networks will have to be developed to bring the CO_2 from the capture facilities to the storage sites in a cost-effective way. There is a need to start planning pipeline networks, coupled to other means of CO_2 transportation and the use of hubs if necessary.

Technical and commercial analyses related to CO_2 transportation networks have been started on the country or regional scale (Rotterdam Climate Initiative and Humberside CCS Network in Europe; National Carbon Mapping and Infrastructure Plan in Australia [Spence, 2009]; CoolGen Project in Japan) and need to be further developed in the coming years. Such analyses will also need to be carried out for other countries and regions with a potential for CCS implementation.

There is also a need to develop legislation that will regulate long-term responsibility with respect to leakage, impacts and liability, financial schemes that will enable commercial player to enter the CCS arena and mapping of a regulatory and permitting approval pathway for all components of the CCS chain, but these topics are outside the scope of this TRM.

SUMMARY OF KEY NEEDS TO START LARGE -SCALE DEMONSTRATION PROJECTS

- Selection of capture technology and engineering for scale up and integration, including reduction of overall energy loss and assessments of environmental impact
- Characterization of the potential storage sites to ensure safe long term storage capacity and containment
- Where it has not been done, conduct an analysis of source/sink distributions and perform an analysis of optimal transport infrastructures to accept CO_2 from different sources in regions or countries where such do not already exist

3.3. Capturing CO_2 from Industrial Sources

R&D on CO_2 capture has focused on the power sector, despite the fact that direct and indirect CO_2 emissions from industry in 2005 equaled that of the power sector, with direct emissions at 70 percent of the power sector (The Organisation for Economic Co-operation and Development and International Energy Agency [OECD and IEA], 2008). There may be several reasons for this, including faster growth rate in the power sector, other means of reducing CO_2 from industrial processes, and that focus in some industries has been on other GHGs.

As pointed out in the IEA TRM (IEA, 2009) variants of the capture technologies may be applicable to industry processes and biomass power plants. Post-combustion is already widely used, particularly in chemical and gas treating plants, and many ammonia plants use technology similar to pre-combustion. Post-combustion capture and oxy-firing with capture may be applicable in iron and steel industry, whereas cement production and refineries may utilize oxy-firing, including chemical looping. In the petrochemical industry the main CO_2 sources are the boilers and Combined Heat and Power (CHP) plants, from which CO_2 removal is similar to other power plants. Chemical absorption technologies may be used in pulp plants for black liquor boilers and the production of heavy oil and tar sands may have use of post-combustion technology to remove CO_2 from steam production and pre-combustion technology to produce hydrogen for upgrading. There will be a need to identify and adapt the CO_2 capture processes best suited for theses industries as well as for the emerging bio-fuels industry.

PRIORITY ACTIVITIES FOR ALL CAPTURE TECHNOLOGIES

- Identify and adapt the most effective options for applications in the oil and gas (refineries and natural gas processing), chemical, steel, aluminum, cement, the emerging bio-fuels as well as other industries

3.4. Retrofitting

If significant reductions in global CO_2 emissions are to be achieved within the next decade, it will be necessary to retrofit with capture facilities power and industrial plants that still have 25 to 30 years of operational life left. As discussed in Section 1.2.4.6, retrofitting these plants is challenging and deserves attention. This is particularly important for coal-fired power stations and for industrial sites.

Proposed standardized definition of a “CCS Ready” plant has been developed jointly by the IEA and the CSLF, in partnership with other leading organizations (IEA/CSLF, 2010), building primarily on the definition by IEA GHG Research and Development Programme (IEA GHG, 2007). ICF International (ICF, 2010a) used a somewhat different definition in a report to the GCCSI and also issued a separate document to GCCSI that provides considerations and recommended practices for policymakers to develop and implement CCS Ready policy and programs, building on the latter definition of “CCS Ready.”

PRIORITY ACTIVITIES FOR ALL CAPTURE TECHNOLOGIES

- Identify requirements, information, and data related to the design, cost, and space operation
- Identify requirements for retrofitting capture technologies at existing power and industry plants and bio-fuel plants (e.g., remove SO_x, NO_x and particulate matter from coal-fired boilers)

3.5. R&D Projects

Although CCS technology is commercially available for certain application today and in use or planned for demonstration projects that will contribute to cost reductions and public awareness of CCS, use of existing technologies may not be sufficient for deployment of CCS on large commercial scales. Basic research is needed to further reduce the costs and achieve affordable large-scale deployment, to improve mapping and understanding the storage potential on scales from global to local, and to close gaps related to public opinion and storage safety as detailed in Chapter 3.6. This requires strong continuous government support.

Cost estimates of CCS are based on a variety of methods and data bases, with the results that estimates of the same concept may differ significantly between institutes and companies. This makes comparisons between technologies and solutions difficult and may hamper implementation. The GCCSI has tried a standardized cost model (GCCSI, 2010). This initial work must be continued and further improved as there is a strong need for such common databases and methods for cost estimation of CCS to remove the uncertainties related to different cost estimation approaches.

CCS technologies are usually treated and evaluated as separate entities without considering their energy, and mass balances and total environmental impacts in a wider perspective. The impact of the whole CCS chain should be analyzed in Life Cycle Assessments (LCA). CCS will reduce emissions of CO_2 but several of the capture technologies and processes may lead to other emissions, discharges and impacts. Examples include added impurities in the off-gases, discharge of cooling water with pollutants like biocide, other waste streams, and noise. Environmental assessments should be undertaken to understand the impacts from such emissions and discharges and keep their impacts at acceptable levels. Although many industries and plants are familiar with handling safety issues associated with gas under pressure and hydrogen as well as health issues related to use of chemicals it will be necessary to perform safety assessments (e.g., IEA GHG, 2009). Health Safety and Environmental (HSE) assessments for existing and new CCS technologies should therefore be carried out in parallel with assessments of energy efficiency and economics.

In view of the expectation of permanent CO_2 storage, the potential liability must be understood so that long-term plans and appropriate levels of monitoring can be put in place. Addressing these issues will contribute to increasing public awareness of CCS technology but falls outside the scope of this TRM.

SUMMARY OF KEY R&D NEEDS TO ASSURE WIDESPREAD DEPLOYMENT

- Acquire sufficient storage resource data to underpin the world-wide location and characterization of viable storage sites
- Accelerate R&D to reduce CO_2 capture cost, efficiency penalties, and transport infrastructure costs
- Further develop common methods and guidelines for cost estimation
- Determine and mitigate any environmental impacts of CO_2 storage
- Perform complete HSE and Life Cycle Assessments (LCA) analysis of capture technologies and full chain CCS systems, including total environmental footprint of different types of power generation with CO_2 capture

3.6. Technology Gaps

3.6.1. CO_2 Capture Gaps

Different capture technologies pose different technical challenges, requiring unique solutions. Common to all technologies is the need to reduce costs and efficiency penalties associated with capture systems. To reach the target of 20 demonstration projects to be launched by 2010 or broad development by 2020, a near-term challenge will be to scale up and integrate existing technologies to full power plant size.

CO_2 capture is currently the most costly component of CCS. Significant process efficiency penalties are associated with capture, which adds to financial pressures associated with CCS. While incremental reductions in capture costs are certainly possible, it is necessary to discover whether large cost savings are possible with this relatively mature technology. If not, different plant configurations, improved separation technologies, or more radical approaches to the capture of CO_2 will be needed to accelerate deployment.

Greater use of biomass is possible, including biomass waste. Co-firing with biomass can give negative emissions due to the way biomass is regarded under greenhouse accounting rules. Use of fast growing biomass from algae is an option that deserves more attention. Burning biomass will introduce different impurities in the exhaust gas than burning fossil fuels. Whereas bio-power is developed and applied worldwide, the combination with CCS is still in the development phase and not operational in large scale. There is a need to identify if and what impacts the impurities in exhaust gas from bio-power will have and to explore use of existing and novel capture technologies.

To obtain better understanding of the new capture systems they must be tested over sufficient time at realistic conditions. Thus, the move from the laboratory scale to pilot scale plants (a few MW) should occur when new technology has proven feasible.

PRIORITY ACTIVITIES FOR ALL CAPTURE TECHNOLOGIES

- Prove technologies at full scale for power plants
- Reduce energy penalty through optimised process design and research into improved and novel capture technologies
- Generate knowledge that is necessary to validate CCS for bio-power, including exploration of use of existing and new capture technologies and evaluate process efficiencies, economics and HSE aspects
- Build understanding of new capture systems by acquiring pilot scale data (2–4 MW)

3.6.2. Post-combustion Capture

Post-combustion capture technologies are widely used in chemical processing and can in principle be applied to flue gases from all kinds of industrial processes, in particular power production from fossil fuels and biomass, cement, steel, and aluminum production. Absorption based on liquid chemical solvents (amines) is currently the leading and most developed technology. Key challenges and long term R&D targets include reduction of the high energy requirement of the separation process and therefore the cost, partly caused by low CO_2 partial pressure (especially for natural gas power plants) and large flue gas volumes. Key elements in research will be to find improved liquid solvents and ways to reduce the size of systems. Another aspect of amines that has recently received attention is the effects of amines emissions on humans and the environment (as demonstrated at a workshop hosted by IEA GHG and Gassnova in Oslo in February 2010). Although research is on-going, this topic needs more attention.

Alternative technologies such as the use of ionic liquids, adsorption by solid sorbents and high temperature carbonate looping cycles, precipitating systems, membrane separation, cryogenic separation and use of biotechnology (e.g., enzymes) are seen as potential candidates. Another new approach (applicable to post-combustion capture as well as pre-combustion capture) is based on gas hydrate crystallization in which CO_2 is incorporated in “cages,” or clathrates. The process is assumed to reduce energy requirements for compression but needs further research.

Exhaust Gas Recycle has been identified as a promising technology for improving the economics of post-combustion capture from Natural Gas Combined Cycle (NGCC, also called Combined Cycle Gas Turbine, CCGT) plants as it may allow size reduction of the amine based separation unit from two to a single train. Some vendors have shown the ability of existing gas turbines to recycle significant amounts of CO_2. However, vendors of post-combustion capture technology now claim ability to design single trains up to capacities in the 550–600 MW equivalent range for natural gas fired power stations. There is a possibility that Exhaust Gas Recycle may not show strong advantages over traditional post-combustion technology for power stations delivering less than 800 MW as believed earlier; however, there is still a need to verify this.

PRIORITY ACTIVITIES

- Further develop improved liquid solvents for CO_2 capture, with reduced energy requirement for regeneration and robustness against impurities
- Identify optimal capture process designs (e.g., integration of components like absorber and desorber and size reductions in general)
- Further develop improved chemical and physical sorbents (e.g., metal organic frameworks and physical sorbents that can be used with different swing adsorption solutions)
- Identify advantages and limitations of precipitating systems (e.g., carbonates)
- Further develop cheaper and more robust membranes with high permeability and selectivity
- Develop enzyme technology for CO_2 separation from mixed gases
- Investigate the use of ionic liquids in the separation process to lower energy use
- Pursue cryogenic and hydrate-based technologies,
- Improve understanding of the effects of NO_x, SO_x, particulate matter, and other impurities in the off-gas from industrial processes and bio-power on the post-combustion capture technologies
- Develop good understanding of environmental impacts from the use of amines and other absorbents in the capture technologies, including impacts on humans and terrestrial and aquatic environments
- Further explore the potential of Exhaust Gas Recycle

3.6.3. Oxy-fuel

This technology is already used on an industrial scale but is currently very costly when applied to CCS, due to the high energy demand for air separation. The first CCS demonstration projects using oxy-fuel technology apply cryogenic air separation (e.g., Schwarze Pumpe and Lacq projects, see also Section 2.3). This will be the only viable air separation technology for large-scale projects in the near future. In longer time perspectives, other air separation technologies based on membranes or adsorbents are seen as potential candidates that may improve the performance of oxy-fuel in the future. Possible ways to improve the efficiency of air separation include cryogenic separation and use of ion-transporting membranes. It may also be possible to integrate the oxygen separation process with the power process.

Although oxy-fuel combustion is being used, there are challenges related to the combustion process, both for boilers and gas turbines. The challenges relate to the design, including fluid- and thermodynamics modeling, and material selection. For boilers there are issues like corrosion, slagging, and fouling.

Chemical Looping Combustion (CLC), regarded as an oxy-fuel solution, has recently seen promising developments for use with natural gas (e.g., Miracca 2009) and should be subject to further studies and improvements.

As the iron and steel and cement industries have an anticipated need for CCS, the use of oxygen instead of air may facilitate simpler and more efficient CO_2 capture from blast furnaces and cement kilns (IEA, 2008 and 2009).

Priority activities should also include technological advances in material science and in process engineering. This will reduce this cost and improve performance and reliability.

PRIORITY ACTIVITIES

- Reduce energy consumption and cost for oxygen production (e.g., advancing cryogenic oxygen production [distillation]) and further develop and qualify high temperature oxygen separating by transport membranes and adsorbents
- Further develop integration of new oxygen separation technologies, e.g., ion-transport and other membranes, with the power process, including the economics and technical issues
- For oxy-fuel combustion:
  - Design of compressor and high-temperature turbines for gas-fired oxyfuel combustion, including operation with a CO_2/H_2O mixture in the working medium
  - Design boilers for higher O_2 concentrations and address issues like corrosion, slagging, fouling, formation of gaseous sulphur species, alternative fuels like low-volatile coals, petcoke, and biomass
  - Undertake R&D on material selections
- Further develop CLC, including improved oxygen carriers and CLC for coal and biomass. Validate scale-up, improve reactor designs and integration in the power process.
- Explore the use of oxy-firing in the cement (kilns in clinker production) and iron and steel industries (blast furnaces)
- Conduct research into the environmental aspects of the oxy-fired plants (e.g., cooling water requirements and purity of liquid effluents)
- Scale-up and validate oxy-fuel plants with low energy penalty

3.6.4. Pre-combustion Capture

Pre-combustion technology is based on well-known technologies that are widely used in commercial operations such as ammonia, hydrogen and syngas production. Pre-combustion capture has been studied extensively for natural gas-fired plants (e.g., Andersen, 2005) but more attention must be directed towards IGCC plants. Although gasification is well known, there are issues connected to scale-up, efficiency and slag and fly ash removal. As IGCC plants may use oxygen-fired reformers, air separation is an issue also in pre-combustion but is considered covered under oxy-fuel.

As for all capture technologies the main challenge is the energy penalty. In addition to the air separation issue, the reforming process has potential both for improved energy efficiency and for more compact designs. This is valid for both the CO or Water Gas Shift (WGS) and the H_2/CO_2 separation processes. For WGS promising results have been achieved using stable solid sorbents (Sorption Enhanced Water Gas Shift, SEWGS) and membrane separation but further research is needed to improve sorbents and, for the membrane alternative, verify and scale up the processes.

Progress has been made in simplification of the process schemes by reducing the number of process steps. Examples include hydrogen membrane reforming, sorption enhanced reforming and a variant of CLC, Chemical Looping Reforming (CLR). Hydrogen membrane reforming (HMR) uses hydrogen-ion-transport or hydrogen permeable membranes to remove hydrogen and reduce the number of process steps, whereas sorption in enhanced reforming (SER) CO_2 reacts with sorbent particles in a gasifier/reformer to form carbonate, combining gasification and shift reaction in one process step. CLR can be used both with conventional steam reforming and as an autothermal reformer. Common to all these technologies is that there is still need for improvements, validations, scale-up, and the effective integration of the key component technologies.

Common to all pre-combustion technologies is the need for turbines that can run on a hydrogen-rich fuel gas with performance and emission levels that equal modern natural gas turbines. Such turbines exist but there is need for further efforts (e.g., to reduce NO_x emissions).

PRIORITY ACTIVITIES

- Up-scale and improve gasifiers, with respect to slag and fly ash removal, efficiency, and amount of gasification agent
- Improve CO or WGS reactors by
  - Further development of shift catalysts, robust towards sour gases
  - Further development and validation of SEWGS using stable sorbents with high cyclic capacity under reaction conditions
  - Further development and validation of membranes (e.g., palladium membranes)
- Further develop and validate hydrogen membrane reformers. The membranes must demonstrate long term durability under operating conditions
- Develop Sorption Enhanced Reforming (SER)
- Further develop and validate steam and autothermal CLR
- Develop high efficiency and low emission H_2 gas turbines, including improved burner concepts and low-emission mode of operation
- Undertake research into full process integration and optimization of the components for power station applications

3.6.5. Emerging and New Concepts for CO_2 Capture and System Studies

To achieve the needed cost reductions and wide implementation of CCS, long-term exploratory R&D in advanced and innovative concepts for the next-generation of CO_2 capture technologies should be emphasized. Several emerging and promising solutions have been mentioned above under each technology category (e.g., chemical looping, post-combustion carbonate looping cycles, gas separation membranes and adsorption processes for CO_2, ion-transport membranes for O_2 separation and enzymatic processes) but the efforts must not stop there. New proposals should be met with an open mind to extend the portfolio of emerging and unproven technology.

One example of an emerging concept is that CO_2 may be fixed biologically in living organisms, and algae show an interesting potential as they grow very fast. Further development of this concept requires characterization of algae species, improved design of photobioreactors and establishing optimum algae growth conditions (temperature, water content, nutrients).

In addition to process- and component-related R&D needs described above there is a need to improve the understanding of overall system related topics (e.g., the technological and economic aspects of large-scale vs. small-scale CCS applications), including small-scale transport and storage of CO_2, or how CCS can be combined with fuel cells and integrated into energy systems.

PRIORITY ACTIVITIES

- Encourage and continuously search for new promising technologies
- Conduct research on CCS and complete energy systems

3.7. CO_2 Transport Gaps

Transportation is the crucial link between CO_2 emission sources and storage sites. CO_2 is likely to be transported predominantly via pipelines. Since 1974, CO_2 has been transported via pipelines in the United States, mainly from natural and anthropogenic sources, to be used for EOR. Today, existing commercial CO_2 pipelines in the United States, with a total length of about 5,650 km, deliver about 68,000 tonnes/day of pressurized CO_2. These pipelines are operated safely through good design and operation and monitoring procedures. Between 1986 and 2008, a total of 13 accidents were recorded, all without injuries to people. Six of the accidents could be blamed on failure of subcomponents like valves and gaskets, two on corrosion, two on operation error, and three had unknown causes. As CO_2 pipeline account for less than 1 percent of total natural gas and hazardous liquids pipelines in the United States, which had 5,610 accidents with 107 fatalities and 520 injuries during 1986–2006, this limited sample indicates that the probability of accidents with CO_2 pipelines is similar to pipelines carrying natural gas (Parfomak and Folger, 2008). It may also be argued that the associated risk is lower since CO_2 is non-explosive and non-inflammable.

Large-scale CCS requires that cost-effective transport networks solutions will have to be developed. Detailed planning of CO_2 transport networks is reliant on a detailed knowledge of the location of technically and economically viable storage sites, which in many regions is contingent on a substantial exploration effort to acquire additional storage data, especially for storage other than in depleted oil and gas fields. There is a need for cost-benefit analyses of complete CO_2 transport networks in different regions, such as Australia's National Carbon Mapping and Infrastructure Plan (Spence, 2009). Large- scale transport networks will present different financial, regulatory, access and development challenges for different regions of the globe where CCS is to be implemented, but these topics are outside the scope of this TRM.

Relative to CO_2 capture, transmission costs are low and the technology problems are reasonably well understood. The preferred mode of transportation of CO_2 is in compressed liquid form in high pressure pipelines. Transmission costs are distance dependent, so the emission source should be located in close proximity to a storage site wherever possible. Long pipelines will incur an energy penalty because they will need booster compression stations. There is limited need for new technology in this area, however, the sheer scale of creating major CO_2 pipeline transmission systems, some of which may to pass through populated areas, will raise financial, legal, institutional, and regulatory issues as well as public concerns. A CO_2 pipeline network, at full deployment, could be similar in size and extent to the existing oil and gas pipeline infrastructure.

Guidelines have recently been issued on pipeline transportation of CO_2 in a broader CCS context (Phase 1 of DNV-led CO_2PIPETRANS joint-industry partnership, DNV 2010b). However, guidelines and standards are based on existing knowledge and key gaps remain. These include knowledge related to the type and amount of impurities in the CO_2 carried in the pipeline and their effects on phase diagrams, thermodynamic and hydrodynamic properties and material selection, as detailed in the list below of priority activities.

Transport of CO_2 by railroad tank cars or truck tankers will be minimal on the global scale but may be an alternative on the local scale or in the case of pilot or small-scale demonstration projects and should be included in future activities. This type of transport may pose stricter safety requirements and better understanding of the risks associated with CO_2 transport, including the possibility and impact of leaks and running pipeline ductile fractures, improved models for the dispersion, and impacts of leaking CO_2 on the environment, including the marine setting, and mitigation measures. The latter may become more important as off-shore CO_2 pipelines are built. Today, there is only one off-shore CO_2 pipeline about 160 km in length (the Snøhvit Field in Northern Norway).

Ship transport of CO_2 is a cost effective alternative for small volumes or long distances for off-shore storage or for seabed transportation. There are few research gaps, and the challenge is more a question of building the ships that are needed. Today, there are few tankers with the necessary capacity and fitness needed for safe CO_2 transport.

PRIORITY ACTIVITIES

- Conduct cost benefit analysis and modeling of CO_2 pipeline networks and transport systems for tankers and trucks
- Issues related to the composition of the gas transported in pipelines:
  - Develop detailed specification with respect to the impurities present from various processes (power station, refineries, industry), which are not present in current CO_2 production units
  - Acquire experimental thermodynamic data for CO_2 with impurities (H_2, SO_x, NO_x, H_2S, O_2, methane, other hydrocarbons etc), develop improved equations of state and establish phase diagram database for the most likely compositions of the CO_2 stream to be transported
  - Understand the effects impurities may have on CO_2 compression and transport, including evaluation of corrosion potentials
  - Gain experience and develop flow models for dense CO_2 streams in pipelines, including de-pressurization
  - Understand the effects of supercritical CO_2 as a solvent on sealing material (e.g., elastomers in valves, gaskets, coatings and O-rings)
- Conduct further research into leaks and running ductile fractures to improve understanding of the effects and impacts of a burst in the pipeline, including experiments and model development
- Improve dispersion modeling and safety analysis for incidental release of larger quantities of CO_2 from the transport system, including the marine setting (e.g., CO_2 pipeline, CO_2 ship, other land transport or intermediate storage tank at harbour)
- Develop proper mitigation measures and design, to ensure safe establishment and operation of CO_2 pipelines through densely populated areas
- Identify and define proper safety protocols for CO_2 pipelines, including response and remediation
- Update technical standards for CO_2 transport as new knowledge become available

3.8. CO_2 Storage Gaps

As discussed in section 1.3, CO_2 can be stored in several types of geological settings, including deep saline formations, depleted oil and gas fields, and deep un-mineable coal seams. To reach the goal of launching 20 industrial-scale demonstration plants by 2010 or broad deployment by 2020, there is an urgent need to demonstrate to governments, the public, regulators, and industry that there is sufficient storage capacity available for large-scale CO_2 projects in various parts of the world and that very large quantities of CO_2 (1–10 Mt/a CO_2 or more per project) can be stored safely for very long periods of time, spanning centuries to millennia. This requirement applies particularly to deep saline formations and to un-mineable coal beds, as the storage capacity and containment ability of oil and gas fields is relatively well defined and understood through oil and gas exploration and production.

3.8.1. Site-specific Issues

Storage is often considered one of the cheaper components of the CCS chain but a critical gap for advancing storage projects and technology is the lack of data and this can require significant resources. There is a need for more site-specific data to underpin the development of demonstration projects and for the operating data from those projects to refine and develop knowledge of storage issues. The information needed include the geology, hydrogeology, geomechanics, geochemistry, pressure, and thermal regimes of proposed storage sites. The data currently available world-wide for the assessment and characterization of storage resources is derived largely from oil and gas exploration. In many regions of the world, particularly those devoid of significant oil and gas resources or in very early stages of exploration, data from oil and gas exploration may be lacking, and a substantial exploration effort, including costly drilling and seismic programs, may be required to locate and characterize viable storage sites.

The time, cost, and resources required to locate viable storage sites, and to then characterize them to the degree of assurance required for multi-billion investment decisions, are often underestimated by governments and many CCS project proponents, especially those without the geological expertise and experience of the oil and gas industry. In addition, the permitting process for approval of storage sites may prove to be quite lengthy, depending on location and acceptance of the local population. Knowledge gained by early-mover projects such as the five existing large-scale projects, the CSLF-recognized Gorgon Project in Australia, and other pilots and demonstrations should be used to close this gap.

Site characterization and monitoring prior to storage (for baseline data acquisition), during injection, and following injection are vitally important. The condition of existing boreholes and their integrity (in terms of sealing/leakage) in the presence of CO_2 must be assessed. Extensive tests to define the volume of the reservoir formation, the thickness and integrity of the cap rock, and the character of any existing faults are desirable prior to injection. For monitoring and verification purposes, background information on CO_2 concentrations at ground level, both off-shore and on-shore, is needed as well as background information on seismic activity in the area.

The operating experience of initial demonstration projects will play a vital role in establishing greater government, industry, and public confidence in storage – both in the general sense of its viability and acceptability, as well as in the technical issues such as storage coefficients and capacity estimation, monitoring, modeling, and verification.

3.8.2. Generic Issues

Capacity Estimation
Although common approaches to storage capacity have been proposed to the CSLF there are still issues to be resolved to obtain commonly agreed methodologies for CO_2 storage capacity estimation. Storage efficiency coefficients display ranges that may result in significantly different capacities if used deterministically. Use of probabilistic assessment methodologies, as used in the oil industry, could be considered as an alternative approach (for application see Spence 2009).

Wells

Wells are considered as an important factor in the overall leakage risk. There is no need to revolutionize well technology, but the potential for cost reductions, without compromising safety, should be sought. However, there are still uncertainties connected to the long-term integrity and reliability of new and existing well bores under CO_2-enriched conditions. This is due to the fact that current knowledge is from well data with relative short lifetime and from laboratory experiments. Furthermore, in Canada and the United States for example, a large number of wells have been drilled over more than a century in potential storage structures. Their condition with respect to cement quality and tightness may pose a considerable challenge to obtain safe long-term storage if the structures are used for CO_2 storage. Thus, there is a need for guidelines or protocols on how to assess and predict well materials and their alterations with time.

It will also be necessary to develop cost-effective mitigation approaches in case of leakages. Standards for how to address leakages must also be established, including clear definitions on liability.

Modeling

The primary technical issues associated with storage are the difficulty of quantifying actual storage capacity; movements of the injected CO_2 and long-term security; verifiability; and the environmental impact of storage. The need to use models to address these issues is recognized as essential and the EC Directive 2009/31/EC on the geological storage of CO_2 describes modeling requirements. Models are used extensively but there are still elements of the models that need improvements, such as better understanding and improved coupling of multi-phased flow, thermodynamics, and geochemistry and geomechanics, the latter including faults and fractures. The injected CO_2 may contain impurities whose impact on flow properties in the reservoir and on geochemical reactions in the reservoir, cap rock, and in wells must be understood and incorporated into the models.

The models must be verified. Presently, there are not sufficient data for this, but as data become available (e.g., from large-scale projects), one needs to establish automated processes for history matching of models and field data.

Monitoring and Verification

Monitoring, verification and mitigation capabilities will be critical in ensuring the long-term safety of storage sites. During injection, the storage site should be fully instrumented to measure reservoir pressure and to detect any escape of CO_2. Fail-safe procedures, perhaps involving CO_2 venting and/or relief wells, should be available in the event of over-pressurization. Methods of monitoring must be capable of imaging and/or measuring the concentration of CO_2 in the reservoir, to verify that the site is performing as required and deliver data for modeling activities. In regard to shallow and atmospheric monitoring, the methods must be sufficiently sensitive to detect CO_2 concentrations only slightly above the background level, and at low leakage rates, and to differentiate between naturally occurring CO_2, including in diurnal and seasonal variations, and stored CO_2. On land, the analysis must be able to distinguish between ground level CO_2 associated with natural processes such as the decay of plant life and that originating from CO_2 injection. Remote sensing and autonomous sampling techniques have the promise of being affordable and able to deliver continuous long-term records. Presently, they have limited use and are neither explored nor exploited sufficiently to qualify for the task.

Research actions should address monitoring of naturally occurring CO_2 accumulations that can provide background information on levels of seepage and the very long-term behaviour of CO_2 in geological formations. It is necessary to update best practice standards and guidelines as R&D results become available.

The extent to which the monitoring capability must remain in place after injection ends and the form of monitoring required are matters to be determined through the development of a proper regulatory and liability framework. Detailed, verified mathematical and numerical models will be important, especially during the post-injection period. Measuring possible leaks and their leakage rates and monitoring the migration of the CO_2 are important issues, not only from a safety and environmental point of view, but also to verify emission trading. All of these developments must recognize the length of time for which secure storage is required.

Monitoring will be subject to site-specific conditions. Off-shore storage sites may be challenging, as they are not easily accessible and monitoring can be expensive when it requires use of ships.

3.8.3. Summary of Gaps in CO_2 Geological Storage

In addition to the needs for improved knowledge described above, there are other topics related to the security of geological storage of CO_2. Risk assessment, including Environmental Impact Assessment (EIA), will play an important role at all stages of activity, not only for planning and when seeking approval for such projects but also in preparing for the post-injection period. The assessments must include likelihood and impacts of CO_2 leakages, including the marine setting wherever the case. Risk assessment techniques must be further developed and verified, which will require more field data, especially from monitored storage projects. Plans for mitigating unwanted situations are part of any comprehensive risk management plan.

The last few years have seen an increase in the publication of guidelines, frameworks, or best practices that cover the whole or part of the CO_2 storage chain (DNV, 2009; CCP, 2009), from planning and site characterization to post-closure monitoring, based on experience from oil and gas wells and a limited number of storage projects and R&D projects. The existing guidelines and standards will have to be consolidated and further developed as experience from more injection and storage projects becomes available.

PRIORITY ACTIVITIES

Site characterization

- Identify and communicate to government, industry, and the public the exploration and characterization requirements and lead times required to underpin the development of demonstration projects

Storage capacity estimation

- Improve storage efficiency coefficients for estimation of effective long-term storage resources at regional and local scales, particularly for deep saline aquifers; this requires greater availability of operational data
- Develop methodological standards to determine practical and matched storage capacities at local scales, particularly for deep saline aquifers

- Modify and adapt probabilistic methods used by the oil industry to assess reserves to estimation of CO_2 storage capacity

Modeling

- Further develop appropriate coupled models that include multi-phase fluid flow, thermo-mechanical-chemical effects, and feedback to predict the fate and effects of the injected CO_2, including faults and other possible leakage pathways
- Improve tools for automated history matching of models with field observations
- Assess long-term post-injection site security using verified mathematical and numerical models of storage

Well integrity

- Further develop (?) protocols for assessing well material alteration and forward simulation of well barrier stability over time
- Develop cost-effective engineering solutions to secure long term well bore integrity, including well design, construction, completion, monitoring, and intervention
- Identify and develop cost-effective well mitigation approaches in case of well leakage

Impurities

- Research the impact of the quality of CO_2 (that is, purity of CO_2 and effects of other compounds) on interactions with the formation brine, reservoir and seal rocks and well cements, and storage behaviour

Monitoring

- Develop low cost and sensitive CO_2 monitoring technologies, including non-intrusive, passive and long term methods, remote sensing and autonomous sampling techniques
- Combine various kinds of methods for improving resolution
- Compile baseline surveys for MMV activities, including site-specific information on CO_2 background concentration and seismic activity
- Develop instruments capable of measuring CO_2 levels close to background and to distinguish between CO_2 from natural processes and that from storage
- Develop cost-effective ways to monitor off-shore sites

Specific gaps in security of geological storage

- Consolidate and further develop best practice guidelines for storage site selection, operation and closure, including risk assessment and response and remediation plans in case of leakage
- Construct maximum impact procedures and guidelines for dealing with CO_2 leaks
- Improve risk assessment tools to identify the likelihood and consequence of CO_2 leaks and inform effective decision making
- Improve understanding of and ability to assess the impacts of CO_2 leakage on ecosystems, including marine settings wherever the case
- Adapt and extend the portfolio of remediation measures, including remediation techniques (foam/ gel, etc.) to maintain or/and restore sealing efficiency, techniques that can be used to divert CO_2 migration pathways from undesired zones and methods to alleviate excessive reservoir pressure

3.8.4. Deep Saline Formations

Deep saline formations represent the largest potential capacity for CO_2 storage and better understanding of their storage capacity and geological, hydrogeological, geomechanical and geochemical properties is required.

Because current knowledge of storage resources is based largely on oil and gas exploration data, there are less data available for deep saline formations than there are for depleted oil and gas fields. Storage- specific exploration is required to fill saline formation data gaps in many parts of the world.

Specific gaps include regional and site-specific knowledge of the sealing potential of the cap rock, of the reservoir formation depth and of its volume and characteristics including storage capacity, trapping mechanisms and efficiency of storage. Continued research into the long-term lateral transport and fate of brine (and consequently the CO_2), including pressure control and variation, water production to regulate pressure, and potential resulting environmental problems is needed. Knowledge on CO_2 migration pathways and timeframes, and determining the volume of rock accessed by a migrating plume, is insufficient. Other areas where more research should be undertaken include the rate and effect of geochemical interactions between CO_2 and rocks and fluids in the reservoir formation and overlying cap rock.

Pressure build-up during CO_2 injection and its effect on injectivity, storage capacity and other potential uses of the aquifer has been flagged as a concern. Water production may be one way to regulate the pressure but, without re-injection into matched aquifers (see Gorgon) it may create other environmental problems.

Remediation actions in case of diffuse CO_2 leakage far from the injection point or pollution of surrounding aquifers will be an important factor in risk management plans and should be paid significant attention.

PRIORITY ACTIVITIES

- Compile a comprehensive assessment of worldwide capacity for CO_2 storage (e.g., in GIS format) in various geological settings and particularly deep saline formations. The compilation must collate and integrate existing national and regional atlases and apply a consistent methodology for storage capacity estimation.
- Conduct a comprehensive assessment of storage resource data required for estimation of practical storage capacity world-wide, and for the location and characterization of viable storage sites that:
  - Identifies key data gaps for the main emissions-intensive regions of the world
  - Identifies the exploration operations required to fill the key data gaps in each region
  - Estimates the time, resources and expenditure required for the exploration operations
- Increase geological knowledge and process modeling performance that:
  - Further investigates the key reservoir and cap rock characteristics of deep saline formations relevant to storage injectivity, capacity and integrity (geometry, structure, mineralogy, fluid chemistry, petro-physics, hydrodynamics, geomechanics, geothermal gradient, etc.)
  - Increases the understanding and modeling of injecting CO_2 into open aquifers (laterally open)
  - Provides tools for predicting spatial reservoir and cap rock characteristics, with assessment of uncertainties
  - Provides a robust storage capacity classification system and informs the legal end of storage licensing procedures
- Increase knowledge regarding relief wells and water production with advantages and disadvantages as a way to regulate the pressure during CO_2 injection utilizing data from the petroleum industry
- Develop guidelines and procedures for handling saline produced water at on-shore as well as off-shore sites

3.8.5. Depleted Oil and Gas Fields

The initial security of reservoirs (implicitly guaranteed by the presence of oil and/or gas) may be compromised in the near well area by drilling, acid treatment, and fracturing during production. Hence, major knowledge gaps include the integrity of abandoned wells (particularly very old or unknown wells which can be adversely affected by corrosion of casing and improper cementing, leading to leakage of CO_2 out of the formation), and understanding of the geochemical reactions between CO_2 and the geological formation. The consequences of reservoir depressurization during production, re-pressurization and possibly over-pressurization during CO_2 storage must be understood, in particular when there are existing faults and/or fractures that may be reactivated and where new fractures may be created. (This is valid also for aquifers since many aquifers are penetrated by exploration and production wells.)

For depleted oil and gas fields, storage projects require site-specific evaluation of reservoirs and seals to identify and quantify the damage caused during hydrocarbon. The integrity of the cap rock must be checked against CO_2 and contained impurities, since the capillary entry pressure is lower for CO_2 than for natural gas or oil, and in the case of some impurities, such as H_2S, is even lower than that of CO_2.

PRIORITY ACTIVITIES

- Consolidate and implement standards for site selection and assessment based on existing best practices and guidelines
- Develop an inventory of oil and gas fields with large storage capacity and an evaluation of the reservoirs and seals within the key fields
- Assess the condition of existing wells and remediation technologies

3.8.6. Un-mineable Coal Seams

Although coal beds may not offer the largest CO_2 storage capacity on a global scale and there have been problems with swelling and need for fracturing, this option may still be of local interest. The major knowledge gaps surrounding CO_2 storage in un-mineable coal seams relate to coal properties including the permeability of certain coal types and the behaviour of coals in the presence of CO_2. Methods for improving the permeability of coals, such as the effectiveness and costs associated with fracturing, need to be assessed. Equally important is the realization that the resource will be sterilized once it is used as a CO_2 sink. Completed research projects include the EU co-funded Recopol project, which showed that it is possible to set up an pilot in Europe and to handle all "soft" issues (permits, contracts, opposition, etc.) related to this kind of innovative project. The lessons learned in this operation can possibly help to overtake start-up barriers of future CO_2 sequestration initiatives in Europe. http://recopol.nitg.tno.nl/index.shtml Research programs on this subject are being conducted by leading research institutions such as the U.S. Geological Survey and National Energy Technology Laboratory (NETL) and the Research Institute of Innovative Technology for the Earth (RITE) in Japan. Pilot projects include the NETL-led Coal-Seq Consortium which aims at studying the feasibility of CO_2 sequestration in deep, un-mineable coal seams using enhanced coalbed recovery technology. http://www.coal-seq.com/index.asp

Though the displacement of methane by various gases, including CO_2, is a relatively well understood phenomenon, greater understanding of the displacement mechanism is needed to optimize CO_2 storage, and more specifically to understand the problem of decreased permeability of coals in the presence of CO_2.

PRIORITY ACTIVITIES

- Assess storage capacity in un-mineable coal seams at local and regional scales
- Better define the mechanisms of methane displacement and permeability decreases following injection of large amounts of CO_2

3.8.7. Mineral Carbonation and Other Storage Alternatives

Mineral carbonation provides a permanent CO_2 storage option. Large quantities of olivine and serpentine rock are found in certain parts of the world, in sufficient quantity to provide large CO_2 storage capacity. This approach to CO_2 storage is at a very early stage of development.

The most common approach to mineral carbonation has been to lead CO_2 through a slurry of the mineral to bind the CO_2 in carbonate and with a by-product that can be used industrially (e.g., silica or cement). Knowledge gaps are associated with the process for converting captured CO_2 into a mineral, for example, increasing in the rate of reaction needed for practical storage. Mass and energy balances are too often missing in studies involving mineral carbonation, as are the environmental impacts of large-scale disposal of the resulting solid material.

Alternatively, the CO_2 can be injected directly into the rock and carbonization can take place in situ (e.g., in basaltic and ultramafic rocks). However, in-situ mineral storage as a method for CO_2 sequestration is significantly less developed than geological storage, and more research is necessary to determine the viability of mineral storage to store large amounts of CO_2. The improvement of reaction rates deserves particular focus.

Shale is the most common type of sedimentary rock that in general has low permeability, which makes it an effective seal. The possibility of and mechanism for achieving economic storage in organic-rich shales should be researched. However, lately the development of oil and gas shale, particularly in North America, may pose challenges to CO_2 storage that need to be explored and understood.

PRIORITY ACTIVITIES

- Build on pioneer studies to further investigate the possibilities of enhancing in-situ mineral trapping of CO_2 and impurities in specific types of settings (basaltic and ultramafic rocks, highly saline aquifers, geothermal reservoirs, shales, etc.) and map these
- Study thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, and geomechanics
- Carry out a techno-economical feasibility studies relating to mineral and shale storage of CO_2
- Study the potential impact of oil and gas production from shales on their potential for storage and on their integrity as a cap rock

3.8.8. Gaps in Uses of CO_2 (EOR, Enhanced Gas Recovery and Enhanced Coal Bed Methane)

EOR, because of the economic benefit of the produced oil, may provide a practical near-term potential for CO_2 storage but will ultimately have niche applications compared to straight storage. Current practices, however, are optimised for oil recovery rather than CO_2 storage and the injected CO_2 at the end of the EOR period is recovered and recycled in subsequent EOR projects. Hence, successful EOR-related CO_2 storage projects need to place equal emphasis on CO_2 storage and oil recovery. Furthermore, EOR must be monitored to be considered CCS and successful EOR-related CO_2 storage projects need the implementation of adequate MMV systems. The concept of Enhanced Gas Recovery of (EGR) needs to be proven and analysed to see if it is beneficial in practice.

Enhanced Coal Bed Methane (ECBM) production provides the opportunity for economic return in conjunction with CO_2 storage in coals. In 2000, a pilot ECBM program was launched at the San Juan Basin's Pump Canyon Test Site in Northern Mexico, USA as part of the U.S. DOE-sponsored Southwest Regional Partnership on Carbon Sequestration. To date, the injection is still ongoing and no CO_2 breakthrough has been recorded, while it is said methane production can be boosted by 70–90 percent.

3.9. Summary of Key Technology Needs and Gaps

ELEMENT: DEMONSTRATION OF COMMERCIAL SCALE PROJECTS	
Need	**Gaps**
20 demonstrations launched by 2010 with broad deployment by 2020	**Scale up** • Scale up and integration of existing technologies into demonstration plants • Integration of existing infrastructure • Experience and information on the design, cost, operation, and integration of CCS with energy facilities and industrial processes **Characterisation of storage sites** • Location and characterisation of viable storage sites to the degree of assurance required for approval of investment decisions and regulatory approval, including public acceptance **Knowledge sharing** • Consistent knowledge sharing between demonstration projects

ELEMENT: CAPTURE R&D	
Need	**Gaps**
Reduce CO_2 capture cost	**Reduced energy penalty** • Absorption solvents or materials that reduce capture costs and increase energy efficiency • Improved chemical and physical sorbents • Improved ion-transport and other membranes and integrate with the power process • Alternative power generation processes that have the potential to produce improved economics compared with absorption capture • Common guidelines and data bases for cost estimation • Identification of most effective solutions for industrial sources • Emerging and new technologies • Proof of technologies at full scale

ELEMENT: TRANSPORT R&D	
Need	**Gaps**
Create the ability to optimize transport infrastructure to accept CO_2 from different sources, to ultimately reduce the risks and high costs	**Pipeline transport** • Better understanding of the behaviour of CO_2 with impurities and the effects on CO_2 transport • Response and remediation procedures developed in advance of the possibility of CO_2 pipeline accidents **Infrastructure planning** • Better modeling capability of transport network of CO_2 between sources and potential sinks, including compression and optimization

ELEMENT: STORAGE AND MONITORING R&D	
Need	**Gaps**
• Demonstrate sufficient CO_2 storage capacity • Ensure safe long-term storage • Develop tools for monitoring and verification of safety and environmental impact	**Storage capacity** • Comprehensive assessment of the gaps in the storage resource data required for estimation of practical storage capacity world-wide **Site selection and operation** • Response and remediation plans on a site-specific basis prior to injection • Consolidation of standards for storage site selection, operation and closure, including risk assessment, and remediation measures, based on existing pest practices and guidelines • Understanding of the effect of existing wells and their condition on site selection, operation, and remediation **Models** • Better models for geological, hydrogeological, geomechanical and geochemical properties of CO_2 storage reservoirs, in particular deep saline formations, including the effect of impurities in the CO_2 stream on the reservoir, cap rock and well materials, and understanding the effects of pressure changes on cap rock integrity and storage capacity • Better understanding of CO_2 mineralisation, including injection into basalt and ultramafic rocks, and of CO_2-coal interactions **Monitoring** • Instruments and methodologies capable of discriminating between CO_2 from natural processes and that from storage

ELEMENT: CROSS-CUTTING ISSUES	
Need	**Gaps**
Establish regulations and standards	**Standards and Best Practice Guidelines** • Risk assessment tools • Good knowledge on environmental impacts of use of solvents in capture systems • LCAs of all parts of the CCS chain and the total system **Regulations** • Energy and emission price issues that would encourage the take-up of CCS • Matched sources and sinks and regional analysis of optimal infrastructures • Regulatory framework for the post-operational (injection) phase of a CCS operation • Liability issues, particularly in regard to the post-operational phase of a CCS operation

MODULE 4: TRM

4.1. The Role of the CSLF

The CSLF, consistent with its Charter, has catalysed the broad adoption and deployment of CCS technologies among participating countries. Since its establishment in 2003, many member countries have initiated significant CCS activities, and the CSLF will continue to promote the development of improved cost-effective technologies through information exchange and collaboration. The CSLF intends to enhance its ongoing and future activities to close the key CCS technology gaps highlighted in this TRM through close collaboration with government, industry, key funding, and support organisations such as the Global Carbon Capture and Storage Institute (GCCSI) and all sectors of the international research community.

4.2. Achieving Widespread CCS Deployment

This roadmap is intended to help set priorities for the CSLF Members by identifying key topics that need to be addressed to achieve the goal of widespread deployment of CCS.

There are still a number of important gaps that need to be addressed and the following over-arching topics are necessary to achieve widespread commercial deployment of CCS:

- Global cooperation within CCS RD&D;
- Launching of 20 large-scale CCS demonstration projects by 2010; and
- Funding of demonstration projects.

The focus of the TRM is on:

- Achieving commercial viability and deployment of CO_2 capture, transport, and storage technologies; reduction in the energy penalty and cost related to CO_2 capture;
- Developing an understanding of global storage potential, including matching CO_2 sources with potential storage sites and infrastructural needs;
- Addressing risk factors to increase confidence in the long-term effectiveness of CO_2 storage; and
- Building technical competence and confidence through sharing information and experience from multiple demonstrations.

Continued RD&D to reduce capture costs and validate safe long-term storage of CO_2 at all levels from theoretical and laboratory work through pilots and large integrated projects is vital. In all aspects, effective knowledge sharing and lessons learned will be key elements that will contribute to the accelerated deployment of CCS. To assist this effort, it will be beneficial to establish guidelines on the type and level of information to be shared that could be applied worldwide in accordance with applicable Intellectual and other property rights. This would help in avoiding problems with sharing of information between countries and regions and so undoubtedly facilitate the global take-up of CCS.

The updated TRM reflects those challenges that need to be addressed, as well as milestones that need to be achieved in order to realize wide scale deployment of CCS post-2020. This is summarized in Figure 14A-C.

The main changes from the 2009 CSLF TRM are:

- Stronger emphasis on CCS integration and demonstration of complete CCS value chains including CO_2 source and capture, transport, and storage of CO_2;
- Stronger differentiation between demonstration and R&D; and
- Expanded and more detailed milestones for capture.

ELEMENT NEED: CAPTURE

Need	2009–2013	2014–2020	Post–2020
• Reduce CO_2 capture cost and efficiency penalties	• Scale-up of existing technologies • Develop guidelines for cost estimation • Research and develop low-energy liquid solvents, adsorbents, and membranes for the three categories of capture technology • Address identified turbine and boiler issues • Achieve good understanding of environmental impacts of capture technologies, in particular amines • Perform system studies of alternative solutions • Harmonize cost estimation methods	• Demonstrate at large-scale existing capture systems • Continue R&D on, and partly validation of, concepts, including • solvents, adsorbents, membranes in post- and pre-combustion and oxyfuel • Chemical Loping Combustion for oxyfuel • Chemical looping Reforming, shift catalysts • R&D and validation of new and emerging technologies	• Validation of capture technologies developed 2014-2020 • Scale-up and integration of technologies validated to commercial scale capture technologies • R&D and validation of new and emerging technologies

ELEMENT NEED: TRANSPORT

Need	2009–2013	2014–2020	Post–2020
• Create the ability to optimize transport infrastructure to accept CO_2 from different sources • Reduce the risks and costs	• Determine allowable CO_2 impurities on CO_2 transport • Establish models to optimize transport networks of CO_2 between sources and potential sinks • Build pipelines linking single CO_2 sources with single storage locations	• Establish technical standards for trans-boundary CO_2 transport • Establish regional networks as examples of multiple source CO_2 transportation	• Establish large infrastructure for CO_2 transport that link multiple CO_2 sources with multiple storage locations

ELEMENT NEED: STORAGE

Need	2009–2013	2014–2020	Post–2020
• Demonstrate sufficiency of CO_2 storage capacity • Validate monitoring for safety and long-term security • Improve understanding of and verify environmental impact	• Develop national and global atlases of CO_2 storage site and capacity • Determine allowable impurities in the CO_2 injected for storage • Establish methodologies for estimating site-specific and worldwide storage capacity • Successfully complete pilot field tests for validation of injection and MMV • Establish methodologies and models for predicting the fate and effects of injected CO_2 and for risk, including well-bore integrity assessment • Initiate large-scale field tests for injection and MMV • Establish industry best practices guidelines for reservoir selection, CO_2 injection, storage, and MMV • Develop remediation measures	• Refine the global atlas of CO_2 storage capacity • Successfully complete large-scale field tests for validation of injection and MMV • Improve best practices for updating industry standards • Commercialize MMV technologies • Validate remediation measures	• Implement commercial operation of storage sites

ELEMENT NEED: INTEGRATION AND DEMONSTRATION			
Need	**2009–2013**	**2014–2020**	**Post–2020**
• Demonstrate, by 2020, fully-integrated commercial-scale CCS projects • Improve awareness and understanding of integrated CCS project development schedules and key tasks	• Initiate large-scale demonstration projects • Develop generic CCS project development schedules and schedule case histories • Engineer scale-up and integration • Locate and characterize storage sites • Build CCS projects database • Ensure sharing of data and knowledge from the 20+ projects currently recognized by CSLF	• Establish operational experience and lessons learned with CCS • Demonstrate integrated next generation technologies • Conduct R&D based on lessons learned • Perform ongoing technology diffusion	• Achieve commercial readiness

4.3. CSLF Actions

The CSLF has been instrumental in stressing the importance of CCS as an indispensable technology in a set of measures to address climate change. The CSLF will continue this role by

- Continuing the partnership with the IEA, the European Technology Platform for ZEP, GCCS, and other stakeholders;
- Facilitating integrated, large-scale commercial scale demonstration projects by actively engaging its members to fund such projects;
- Encouraging its members to identify, assess and prepare safe storage sites;
- Encouraging its members to pursue and fund initiatives and activities that include
  - Conducting R&D work to address the technological gaps and priorities that have been identified; in this TRM
  - Continuing to build capacity within research and development, engineering and education
  - Ensuring that the appropriate level of resources is identified to fill these gaps.
  - Ensuring technology diffusion to achieve worldwide CCS deployment
  - Building best practice guidelines, standards, and methodologies and setting up information flows across all aspects of CO_2 capture, transport, storage, and integration
  - Increasing public communication to increase the public knowledge of CCS; and
- Working to overcome hurdles regarding regulatory and financial issues.

Figure 14A. A summary of the key milestones and TRM for the CSLF Presently. Improved cost-effective technologies and long-term safe storage of CO$_2$.

	PRESENT
DEMONSTRATION AND INTEGRATION	• Initiate large-scale demonstration project • Engineer scale-up and integration • Locate and characterize storage sites • Build CCS projects database
CAPTURE R&D	• Scale-up of existing technologies • Develop guidelines for cost estimation • Research and develop low-energy liquid solvents, adsorbents and membranes for the three categories of capture technology • Address identified turbine and boiler issues • Achieve good understanding of environmental impacts of capture technologies, in particular amines • Perform system studies of alternative solutions • Harmonize cost estimation methods
TRANSPORT R&D	• Determine allowable CO$_2$ impurities on CO$_2$ transport • Establish models to optimize transport network of CO$_2$ between sources and potential risks
STORAGE R&D	• Determine allowable impurities in the CO$_2$ for storage • Establish methodologies for estimating storage capacity and develop national and global storage atlas • Successfully complete pilot field tests for validation of inject6ion and MMV • Well bore integrity and for risk assessment • Initiate large-scale field tests for injection and MMV • Establish industry best practices guidelines for reservoir selet6ion, CO$_2$ injection, storage, and MMV • Develop remediation measures

Figure 14B. A summary of the key milestones and TRM for the CSLF in 2013. Improved cost-effective technologies and long-term safe storage of CO_2.

	2013
DEMONSTRATION AND INTEGRATION	• Establish operational experience and lessons learned with CCS • Demonstration integrated next generation technologies • Conduct R&D based on lessons learned • Ongoing technology diffusion
CAPTURE R&D	• Demonstrate at large-scale existing capture systems • Continued R&D on, and partly validation of concepts, including solvents, adsorbents, membranes in post- and pre-combustion and oxyfuel • Chemical Loping Combustion for oxyfuel • Chemical looping Reforming, Shift catalysts
TRANSPORT R&D	• Establish technical standards for trans-boundary CO_2 transport • Establish regional networks as examples of multiple source CO_2 transportation
STORAGE R&D	• Refine global atlas of CO_2 storage capacity • Successfully complete large-scale field tests for validation of injection and MMV • Improve best practices for updating industry standards • Commercialise MMV technologies • Validate remediation measures

Figure 14C. A summary of the key milestones and TRM for the CSLF in 2020. Improved cost-effective technologies and long-term safe storage of CO_2.

	2020
DEMONSTRATION AND INTEGRATION	• Achieve commercial readiness
CAPTURE R&D	• Validation of capture technologies developed 2014–2020 • Scale-up and integration of technologies validated to commercial scale capture technologies • R&D and validation of new and emerging technologies
TRANSPORT R&D	• Establish infrastructure emplacement for CO_2 transport
STORAGE R&D	• Implement commercial operation of storages sites

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Glossary of Acronyms, Abbreviations, and Units

A$	Australian dollars
ADEME	French Environment and Energy Management Agency
ADM	Archer Daniels Midland
ANR	National Research Agency
ARRA	American Reinvestment and Recovery Act
BSIK	Besluit Subsidies Investeringen Kennisinfrastructuur (Dutch Subsidy Program)
C$	Canadian dollars
CACHET	European Commission Research Project
CANMET	Canada Centre for Mineral and Energy Technology
CAPTECH	CO_2 Capture Technology Development, Dutch Research Program
CAS	Chinese Academy of Sciences
CASTOR	CO_2 from Capture to Storage – European Initiative
CATO	Carbon Capture, Transport and Storage
CCGT	Combined Cycle Gas Turbine
CCP	CO_2 Capture Project
CCS	CO_2 capture and storage
CDRS	Carbon Dioxide Reduction & Sequestration
CEP	Center for Energy and Power
CERP	Carbon Efficient recovery and processing
CERTH/ISFTA	Centre for Research and Technology Hellas/Institute for Solid Fuels Technology and Application
CESAR	Center for Engineering Science Advanced Research
CETC	CANMET Energy Technology Centre
CFE	Federal Electricity Commission (Mexico)
CHP	Combined Heat and Power
CLC	Chemical Looping Combustion
CLR	Chemical Looping Reforming
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2CRC	Cooperative Research Centre for Greenhouse Gas Technologies
COE	Cost of energy
COORETEC	CO_2 – Reduction – Tecnologies
CPRS	Carbon Pollution Reduction Scheme
CSLF	Carbon Sequestration Leadership Forum
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
ECBM	Enhanced coal bed methane
EC	European Commission
ECBM	Enhanced Coal Bed Methane
ECN	Energy research Centre of the Netherlands
EEPR	European Energy Programme for Recovery
EGR	Enhanced gas recovery
EIA	Environmental Impact Assessment
ENCAP	Enhanced CO_2 Capture Project
EOR	Enhanced oil recovery
EOS	Energy Research Strategy (Program of the Dutch government)
ESA	Electric Swing adsorption
ETP	European Technology Platform
ETS	Emissions trading scheme

EU	European Union
EUETS	European Union Emission Trading System
FENCOERA.NET	The Fossil Energy Coalition
FID	Final Investment Decision
FOAK	First-of-a-Kind
GCCSI	Global Carbon Capture and Storage Institute
GEUS	Geological Survey of Denmark and Greenland
GESTCO	European Potential for the Geological Storage of CO_2 from Fossil Fuel Combustion
GHG	Greenhouse Gas
GIS	Geographic information system
Gt	Gigatons (10^9 tons)
H_2	Hydrogen
H_2S	Hydrogen Sulphide
HARP	Heartland Area Redwater CO_2 Storage Project
HECA	Hydrogen Energy California Project
HMR	Hydrogen Membrane Reforming
HSE	Health Safety and Environmental
IEA	International Energy Agency
IEA GHG	IEA Greenhouse Gas
IGCC	Integrated Gasification Combined-Cycle
IIE	Institute of Electrical Research
INRS	Institut National de la Recherche Scientifique
IP	Intellectual property
IPAC-CO_2	International Performance Assessment Centre for Geologic Storage of CO_2
IPCC	Intergovernmental Panel on Climate Change
ITC	International Test Center for CO_2 Capture
ITM	Ion Transfer membrane
KEPRI	Korea Electric Power Research Institute
kg	Kilograms
km	Kilometers
KAPSARC	King Abdullah Petroleum Studies and Research Centre
KAUST	King Abdullah Petroleum University of Science and Technology
LCA	Life Cycle Assessments
LCOE	Levelised Cost of Electricity
LHV	Lower heating value
LNG/LPG	Liquefied Natural Gas/Liquefied Petroleum Gas
KWh	Kilowatt-hour
m	Meters
mtpa	Million tonnes per year
MEST	Ministry of Education, Science & Technology
mg/L	Milligrams per litre
MGSC	Midwest Geological Sequestration Consortium
MKE	Ministry of Knowledge Economy
MPa	Megapascals, SI unit of pressure (10^6 pascals)
Mt/a	Megatonnes per annum (millions of metric tons per year)
$MtCO_2$	Megatonnes of carbon dioxide
MILD	Moderate and/or Intensive Low Oxygen Combustion
MMV	Measurement, Monitoring and Verification
MW	Megawatts, SI unit of power, subscript $_{th}$ denotes thermal capacity, $_e$ denotes Electrical

MW_e	Megawatts, SI unit of power, subscript, $_e$ denotes Electrical
MWh	Megawatt hour
MW_{th}	Megawatts, SI unit of power, subscript $_{th}$ denotes thermal capacity
N_2	Nitrogen
NETL	National Energy Technology Laboratory
NGCC	Natural Gas Combined Cycle (also referred to as CCGT – Combined Cycle Gas Turbine)
NH_3	Ammonia
NOAK	Nth of a Kind
NZEC	Near-Zero Emissions Coal
O_2	Oxygen
OECD	Organization for Economic Co-operation and Development
OSPAR	Commission (European Based)
PC	Pulverised Coal (sometimes referred to as PF – Pulverised Fuel)
PCC	Pulverized Coal Combustion
PCOR	Plains CO_2 Reduction Partnership
PSA	Pressure Swing adsorption
PTRC	Petroleum Technology Research Centre
R&D	Research and Development
RCSP	Regional Carbon Sequestration Partnerships
RD&D	Research, development, and demonstration
RCI	Rotterdam Climate Initiative
RISCS	Research in impacts and safety in CO_2 Storage
RITE	Research Institute of Innovative Technology for the Earth
ROAD	Rotterdam Afvang en Opslag Demo
SER	Sorption in Enhanced Reforming
SEWGS	Sorption Enhanced Water Gas Shift
SRA	Strategic Research Agenda
TCM	Technology Center Mongstad
TRM	Technology Roadmap
TSA	Temperature Swing adsorption
UCE	Ultrecht Centre for Energy Research
US$	U.S. Dollars
USA	United State of America
ULCOS	Ultra Low Carbon Dioxide Steelmaking
ULYSSES	Undersea Large-scale Saline Sequestration and Enhanced Storage
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WGS	Water gas shift
ZEP	Zero Emission Platform
ZEP	Zero Emission Fossil Fuel Power Plants
ZEPP	Zero Emission Power Plant