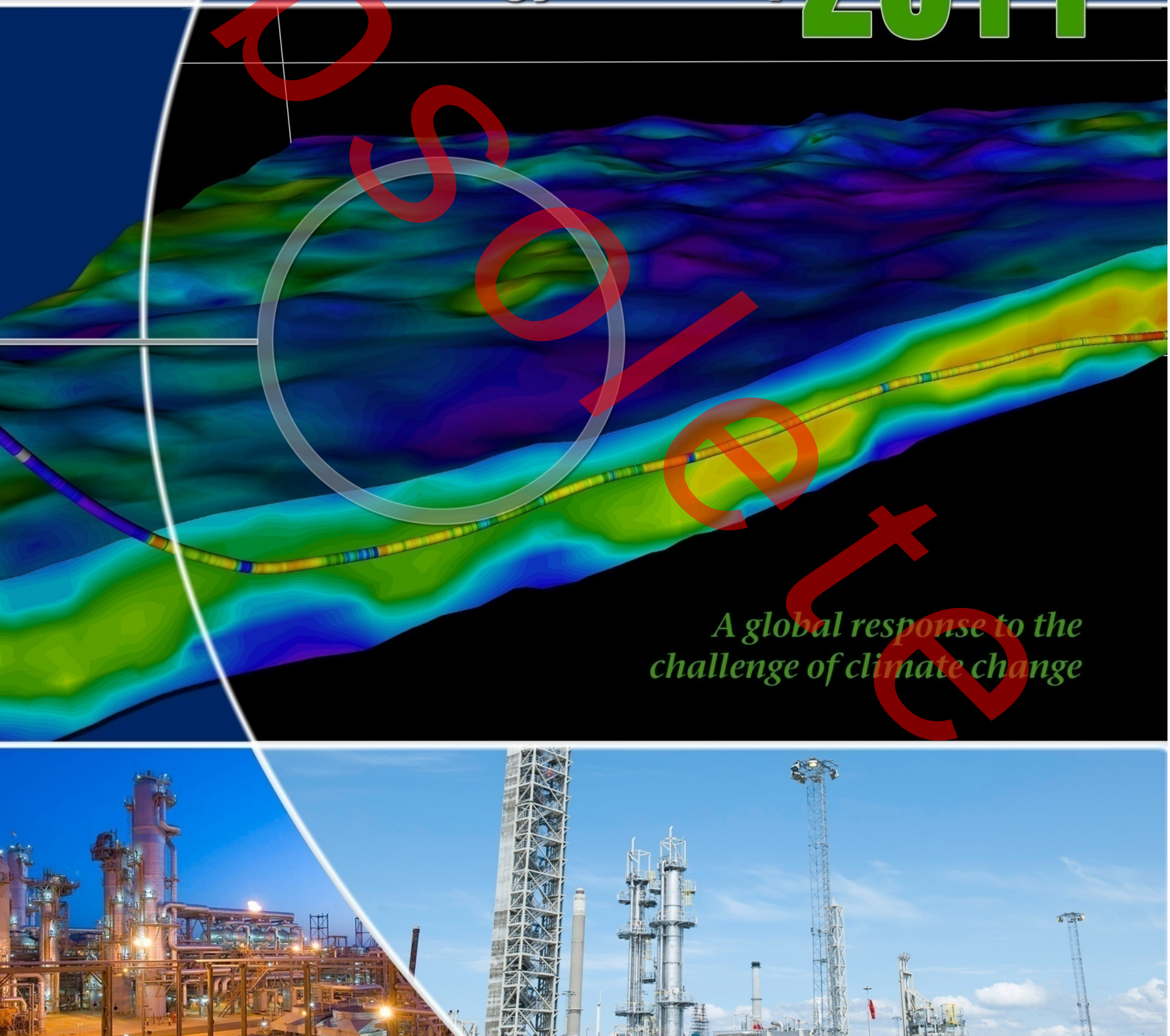
carbon
sequestration leadership forum

Carbon Sequestration Leadership Forum

Technology Roadmap 2011



A global response to the challenge of climate change

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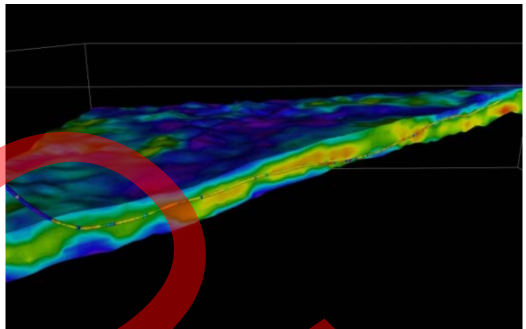

ABOUT THE COVER

Front Cover—

3D Model of KB 503 Well Trajectory, In Salah; Seismic imaging process uses sound waves to create a detailed picture of the subsurface.

In Salah Carbon Capture and Storage Project, Amine Towers Central Processing Facility. In Salah, an industrial-scale CCS project has been in operation since 2004. More than three million tons of CO_2, have been securely stored in a deep saline formation.

The Amine Towers at Technology Centre Mongstad (TCM). One of the technologies chosen by TCM is a post-combustion capture technique using amines.

Back Cover—

View of pipe racks at TCM. The 1 m large-diameter pipes will transport the gas from the refinery and power plant to the capture plants.

The Doosan Power Systems 96 MWth Clean Combustion Test Facility (CCTF) based at Renfrew Scotland, during the development of our 40MWt OxyFuel Burner and systems.

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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 effectively 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 and 2010 to take into account the significant CCS developments that occurred during the 2004 to early 2009 period and identify key knowledge gaps and areas where further research should be undertaken. The 2011 TRM places a stronger emphasis on:

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

Significant CSLF project activity occurred in the period from 2004 to 2011, and substantial progress has been made in all aspects of CCS. For example, there are now 30 active or completed CSLF-recognized projects demonstrating worldwide collaboration on CCS and contributing to the CCS knowledge base. Completed projects include the following:

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

Active projects include the following:

- CANMET Energy Technology Centre (CETC) R&D Oxyfuel Combustion for CO_2 Capture
- CCS Bełchatów Project
- CCS Northern Netherlands
- CCS Rotterdam
- CO2CRC Otway Project
- CO_2 Field Lab Project
- CO_2 GeoNet
- CO_2 Separation from Pressurized Gas Stream
- Demonstration of an Oxyfuel Combustion System
- European CO_2 Technology Centre Mongstad
- Fort Nelson Carbon Capture and Storage Project
- Geologic CO_2 Storage Assurance at In Salah, Algeria
- Gorgon CO_2 Injection Project
- IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project
- ITC CO_2 Capture with Chemical Solvents
- Lacq CO_2 Capture and Storage Project
- Quest CCS Project
- Regional Carbon Sequestration Partnerships
- SECARB Early Test at Cranfield Project
- Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project

At the time of this writing, several medium scale (10–50 megawatt [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). Although the summary is based on studies issued by IEA GHG in the period 2005 to 2009, the findings are universal. One finding is that for post-combustion capture, solvent scrubbing is considered state-of-the-art and 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 to 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 utmost 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 several years, is about 160 kilometers (km) long and transports 0.7 million tonnes per year (Mt/a) 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 as to 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 CCS 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:

- Achieve commercial viability and integration of CO_2 capture, transport, and storage through technologies and learning opportunities;
- 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 of facilitating 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 commercialization 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.

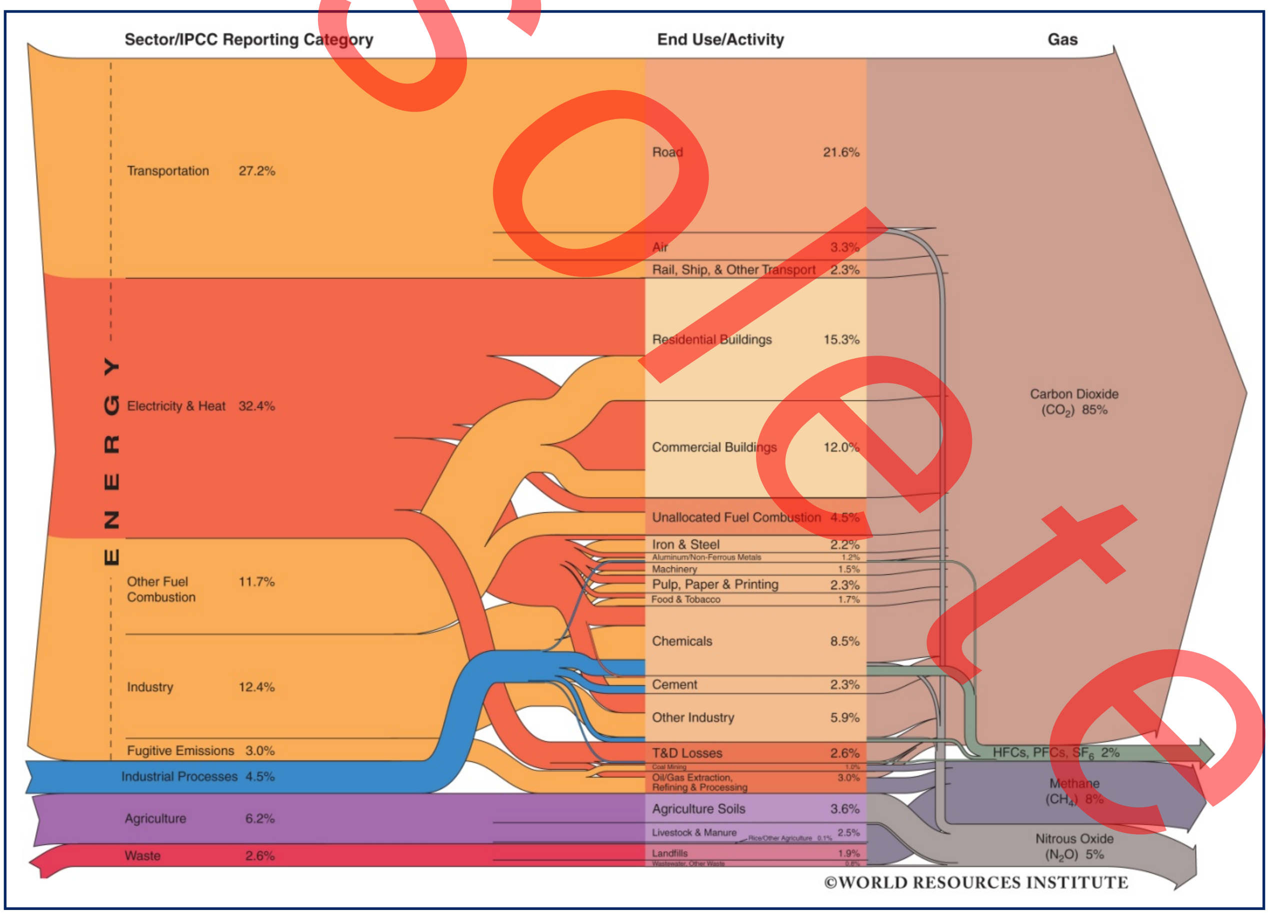

Figure 1. World emissions flow chart (World Resources Institute, 2005)

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 tons of CO_2 per hour, while a modern natural gas-fired combined cycle (NGCC) plant of the same size will emit about 180 tons per hour of CO_2 in flue gases. The respective CO_2 concentrations in flue gases are about 14 percent (by volume) for a coal-fired plant and four 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 over 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 (ULCOS) program 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 to 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 oxy-fuel 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 desulfurization, 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 Figures 2 and 3.

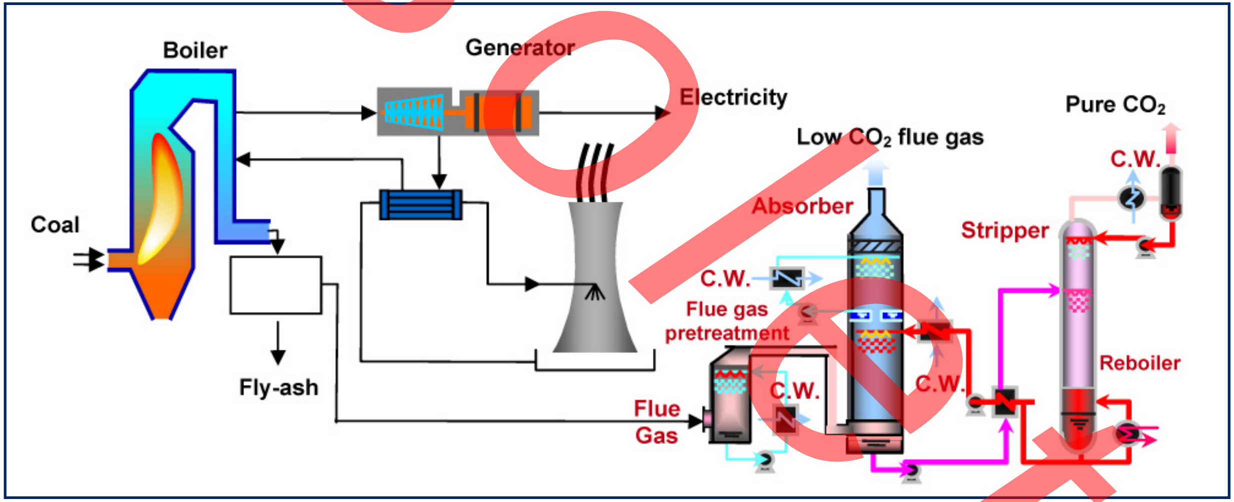

Figure 2. Coal-fired power station with post-combustion capture of CO_2 (courtesy of the Commonwealth Scientific and Industrial Research Organisation)

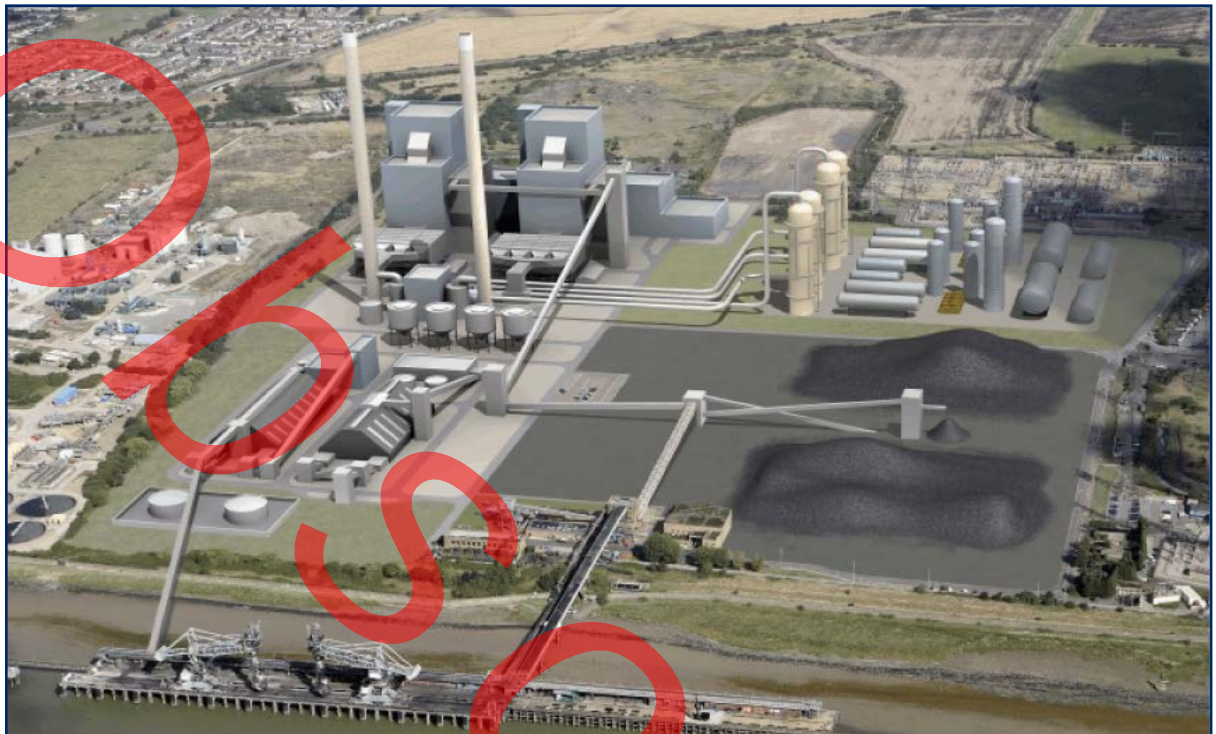

Figure 3. 2x800 MW UK coal-fired power station with capture — shown behind the coal stockpiles (sourced from Imperial College, London and RWE Group)

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.

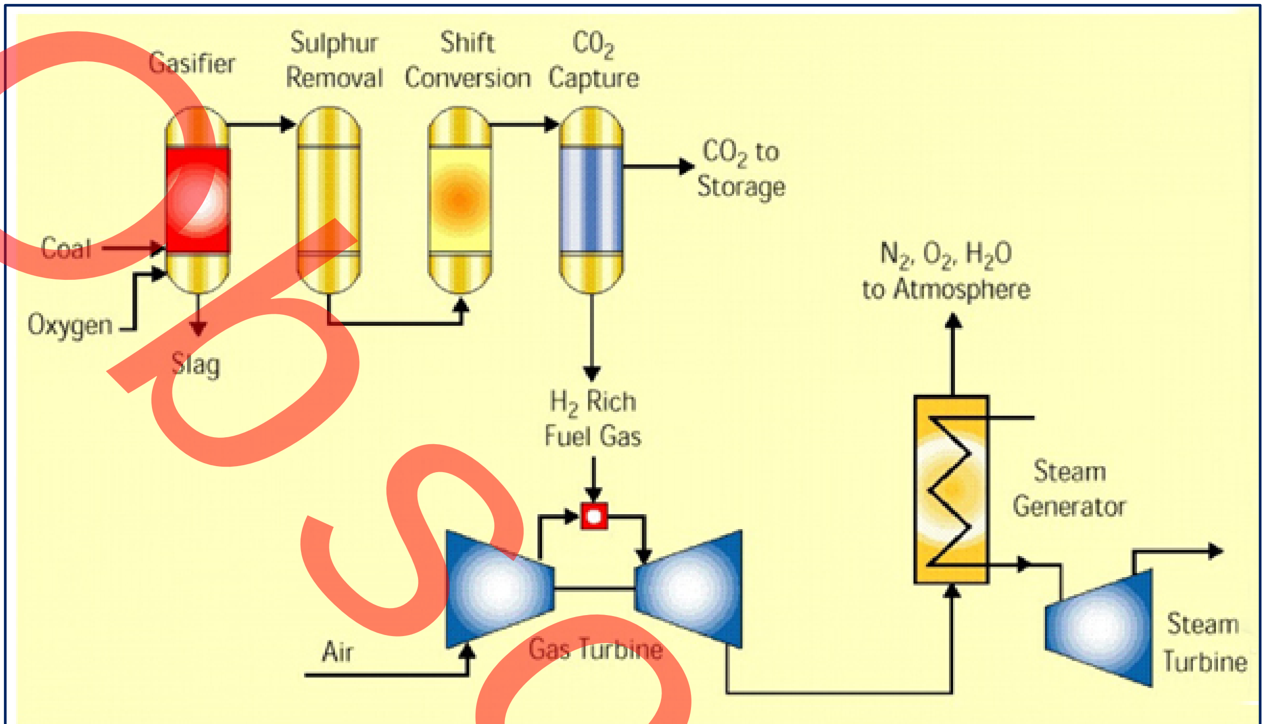

Figure 4. Coal-fired Integrated Gasification Combined Cycle (IGCC) process with pre-combustion capture of CO_2 (courtesy of the IEA GHG R&D Programme)

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 more than 60 years in the energy, refining and chemical industries for removal of hydrogen sulfide (H_2S) and CO_2 from sour natural gas and reducing gases. Only a few facilities use amines to capture CO_2 from oxidizing 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 to 40 percent and a total pressure of 20 bar or more. Under these pre-combustion conditions, physical solvents that result in 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 oxidized 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-oxidized 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. Sulfur 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. In case of the Schwarze Pumpe Oxyfuel pilot plant of Vattenfall in Germany, for example, there was transportation of CO_2 in liquid stage by trucks to the CO_2-storage project CO_2Sink/CO_2Man in Ketzin (distance about 200 km). From May until June 2011 about 2,000 tonnes of CO_2 were transported and stored in this campaign. However, only pipeline and tanker transmission are commercially reasonable options for the large quantities of CO_2 associated with centralized collection hubs or point source emitters such as power stations of 500 MWe capacity or greater.

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 Mt/a of CO_2 are transmitted through more than 5,650 km 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.

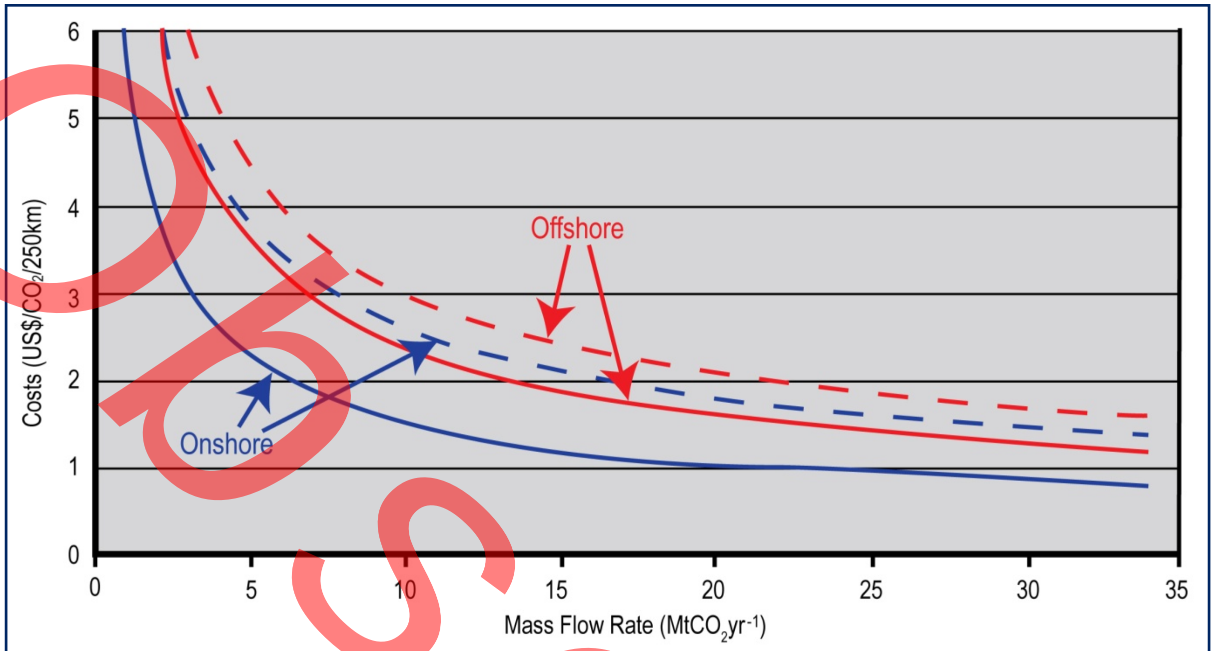

Figure 5. Range of CO_2 transport costs for on-shore and off-shore pipelines per 250 km. Solid lines show low range values and dotted lines high range values (Source: OECD/IEA, 2008)

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 1,500 cubic meters (m^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 liquefied natural gas (LNG) and/or liquefied petroleum gas (LPG) transport as a pressurized 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 6 Mt/a of CO_2 over a distance of 500 km by ship would cost about US$10/tonne of CO_2, while transporting the same amount of CO_2 a distance of 1,250 km would cost about US$15/tonne of 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;
- By injecting it into the ocean; and
- Through mineralization and industrial use.

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 un-mineable 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 megapascals (MPa), which occurs approximately 800 meters below surface level where it has properties of both a gas and a liquid and is 500 to 600 times more dense (up to a density of about 700 kg/m^3) than at surface conditions, while remaining more buoyant than formation brine. CO_2 can also be injected into un-mineable coal beds where it is stored by adsorption onto the coal surface, sometimes enhancing coal bed methane production.

Frio CO_2 Geological Storage R&D Project demonstrates the feasibility of geologic sequestration in saline aquifers.

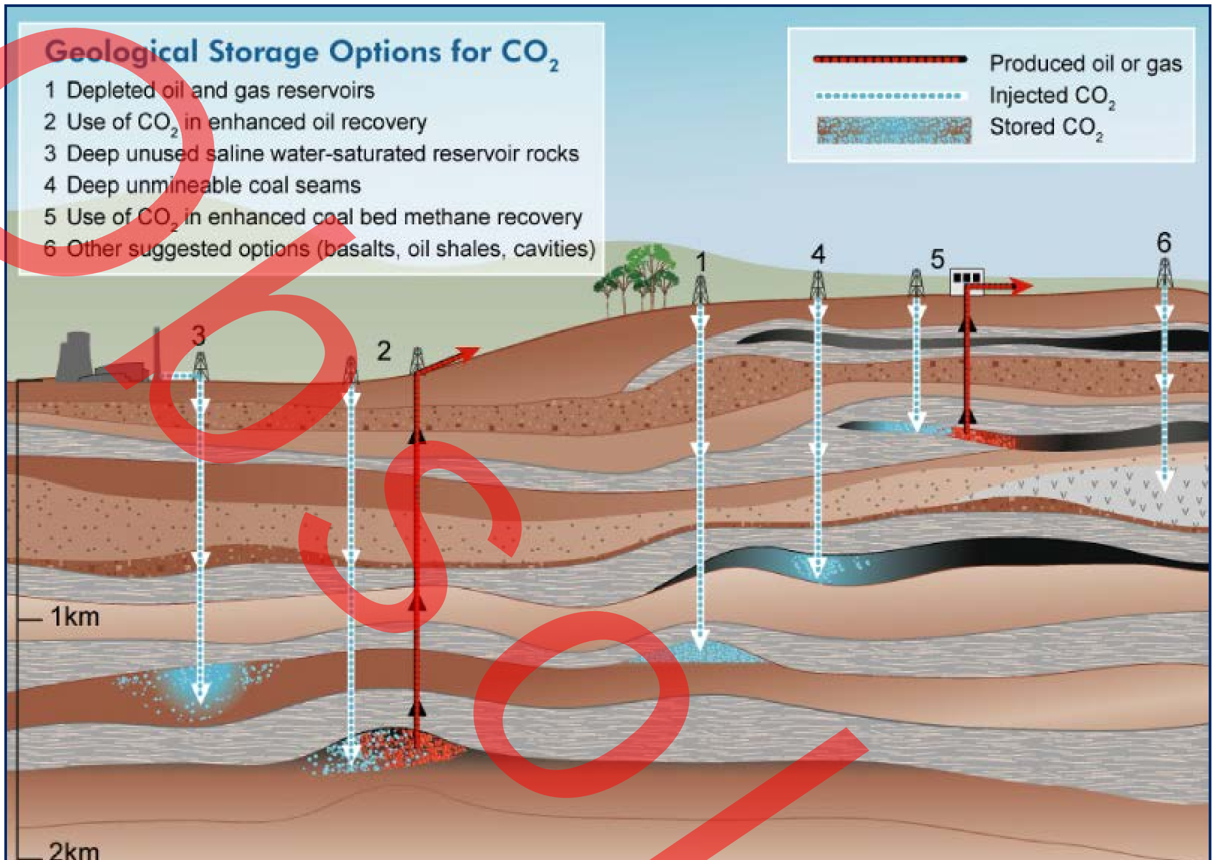

Figure 6. Geological options for CO_2 storage (courtesy of the Cooperative Research Centre for GHG Technologies)

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 1 Mt/a of CO_2 (captured from a natural gas stream) into the Utsira Formation at a depth of about 1,000 meters below the sea floor, began in 1996. The CO_2 is being monitored through an international project established by Statoil with the IEA GHG R&D Programme (Statoil, 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 Mt/a of CO_2 have been injected into the aquifer portion of the gas reservoir at a depth of 1,800 meters (Statoil, 2008); and
- The Snøhvit LNG project in the Barents Sea, where, since 2008, 0.7 Mt/a of CO_2 have been stored in a saline formation 2,500 meters beneath the sea floor (Statoil, 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 to 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. Un-mineable Coal Beds

Coal beds below economic mining depth could be used to store CO_2. CO_2 injected into un-mineable 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 greenhouse gas (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 600 and 1,000 meters, and less than 1,200 meters. Shallow beds less than 600 meters deep have economic viability and beds at depths greater than 1,000 meters 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 milligrams per liter (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 un-mineable coal beds has been, 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. Mineralization

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 mineralization 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 Organization stated that CO_2 can only be disposed of in a sub-seabed geological formation (International Maritime Organization, 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 two decades.

With gas re-injection, either for storage or EOR, reservoir over-pressurization 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 practice, 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 mineralization, 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 behavior 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 to 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 to 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 Mt/a of CO_2 and transports it 330 km 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 Mt/a of CO_2 are injected for EOR at the Cenovus and Apache fields at Weyburn, with approximately 35 million tonnes of CO_2 expected to be stored over the course of the project (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 at least 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, fertilizers, 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 fertilizer 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 un-mineable 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 un-mineable 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 shows estimates of CO_2 storage costs.

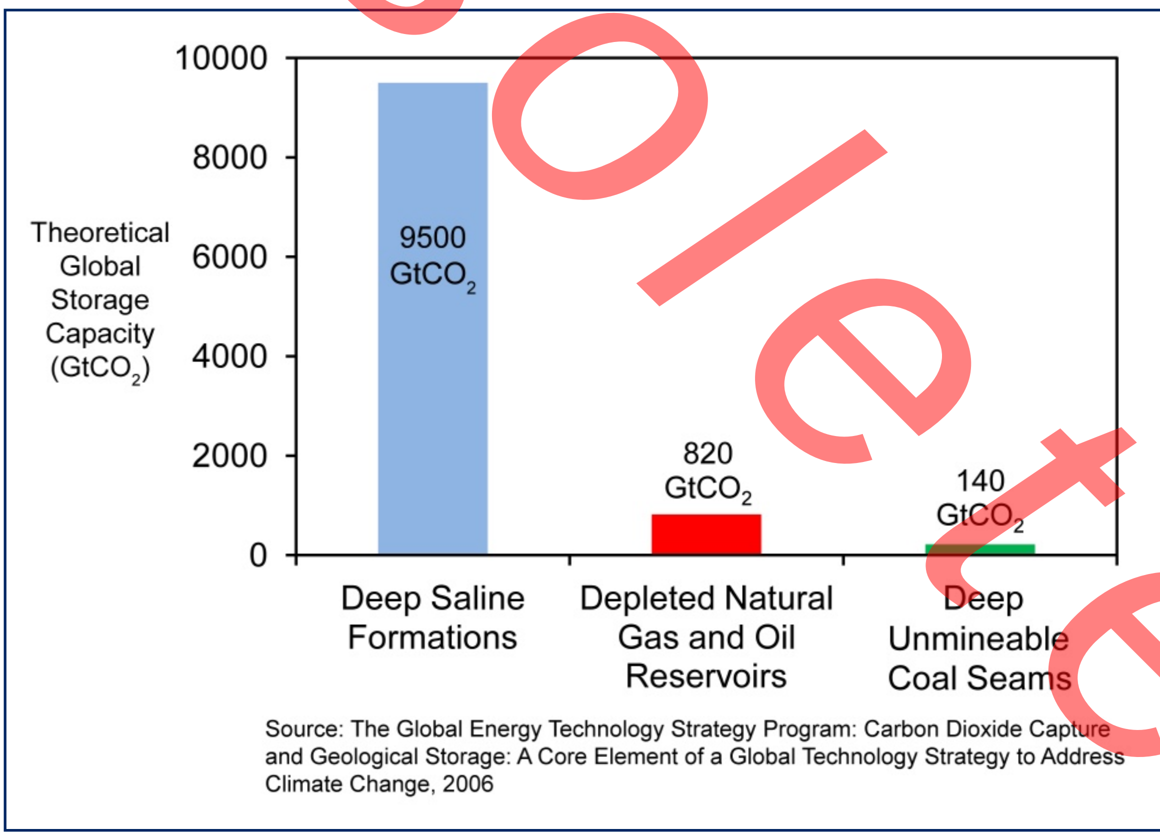

Figure 7. The theoretical global storage capacity of CO_2

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 organizations have evaluated the performance and costs of power generation options with and without CO_2 capture. These sources have been utilized 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 pulverized coal fuel (PC), IGCC, and 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.

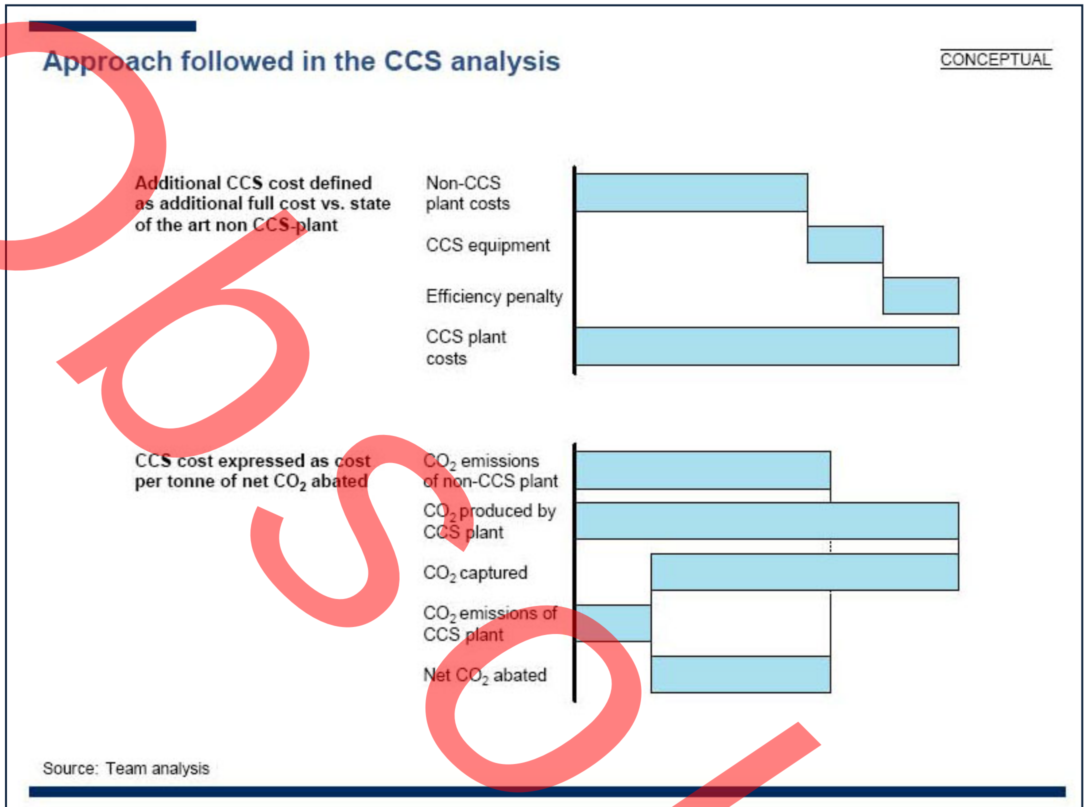

Figure 9. The conceptual costs associated with CO_2 capture for power stations

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.

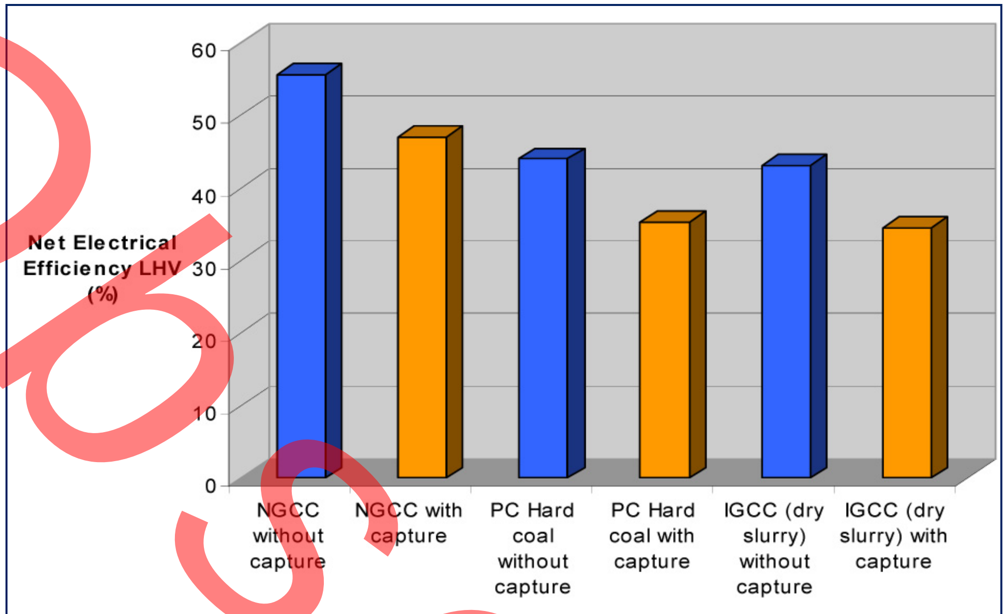

Figure 10. Power station generation efficiencies with and without the capture of CO_2 (Source: IEA GHG R&D Programme, 2007)

Economic modeling in the Global CCS Institute 2009 Strategic Analysis of the Global Status of CCS, which is summarized in the table below on page 33, determined that the cost of CCS for power generation, based on the use of commercially available technology, ranged from US$62 to US$112 per ton of CO_2 avoided or US$44 to US$90 per ton of CO_2 captured. The lowest cost of CO_2 avoided was at US$62 per ton of CO_2 for the oxyfuel combustion technology, while the highest cost at US$112 per ton 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 US$44 per ton of CO_2 and the highest of US$90 per ton 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.

The table below 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 (US$18), and fertilizer production (US$18) followed by cement production (US$50) and blast furnace steel production (US$52).

The table below 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 (one percent) followed by fertilizer 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 levelized 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 three to ten percent and a resulting decrease in the LCOE of less than five 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 ten 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 characterization represent a significant risk to the project and can increase storage costs from US$3.50/ton CO_2 to US$7.50/ton 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.

SUMMARY OF ECONOMIC ASSESSMENT OF CCS TECHNOLOGIES									
	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
Levelised Cost of Production	Dimensions	US$/ MWh	US$/ MWh	US$/ MWh	US$/ MWh	US$/ton steel	US$/ton cement	US$/GJ natural gas	US$/ton ammonia
	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] (\$/ton 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 (\$/ton CO_2)	FOAK	56–57	44–51	44	90	52	50	18	18
	NOAK	54–55	42–49	42	87	47	47	18	18

Notes:
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

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MODULE 2: ONGOING ACTIVITIES IN CO_2 CAPTURE AND STORAGE

2.1. Introduction

This module summarizes ongoing activities on the capture and storage of CO_2. Figure 11A shows Active or Planned Large-scale Integrated Projects by Capture Facility, Storage Type, and Region; Figure 11B and 11C shows similar information for North America and Europe, respectively.

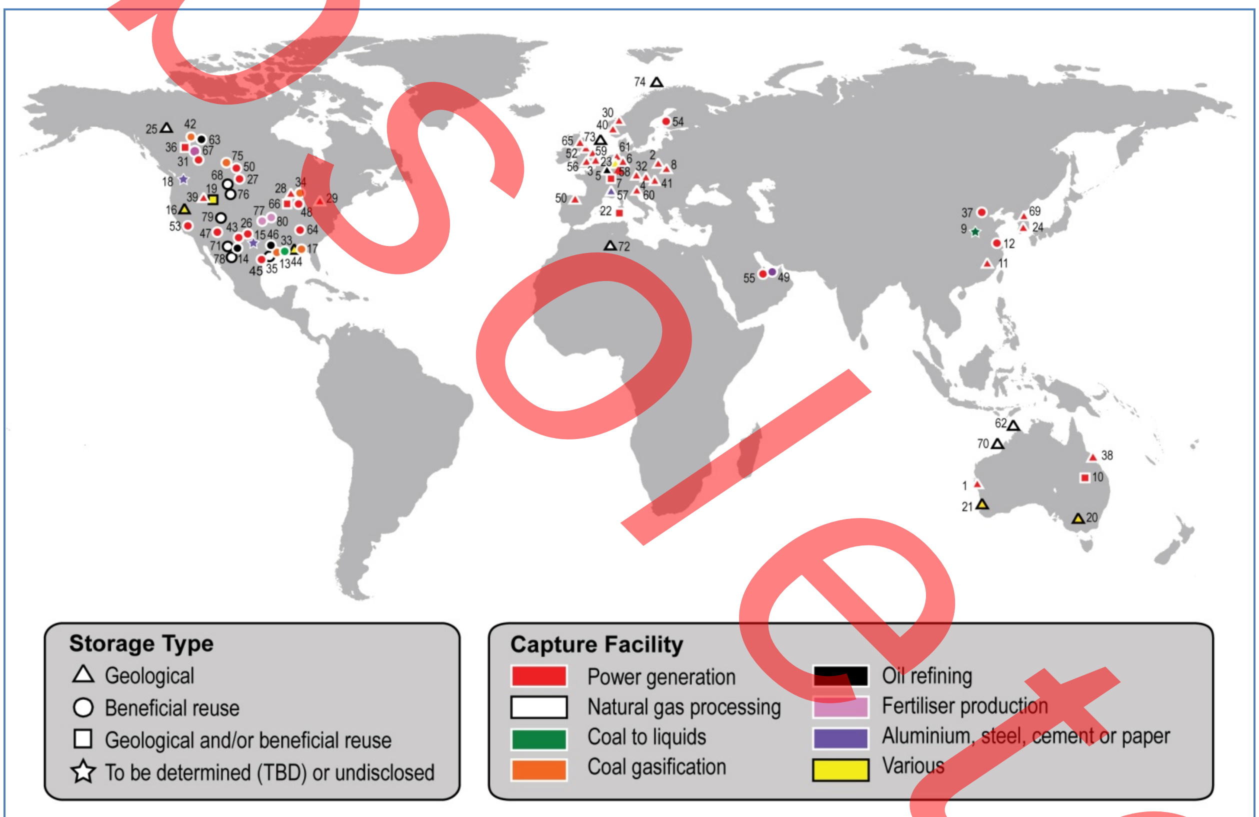


Figure 11A. Active or planned large-scale integrated projects by capture facility, storage type and region (Source: Global CCS Institute 2010) [Note: project numbers refer to GCCSI report]

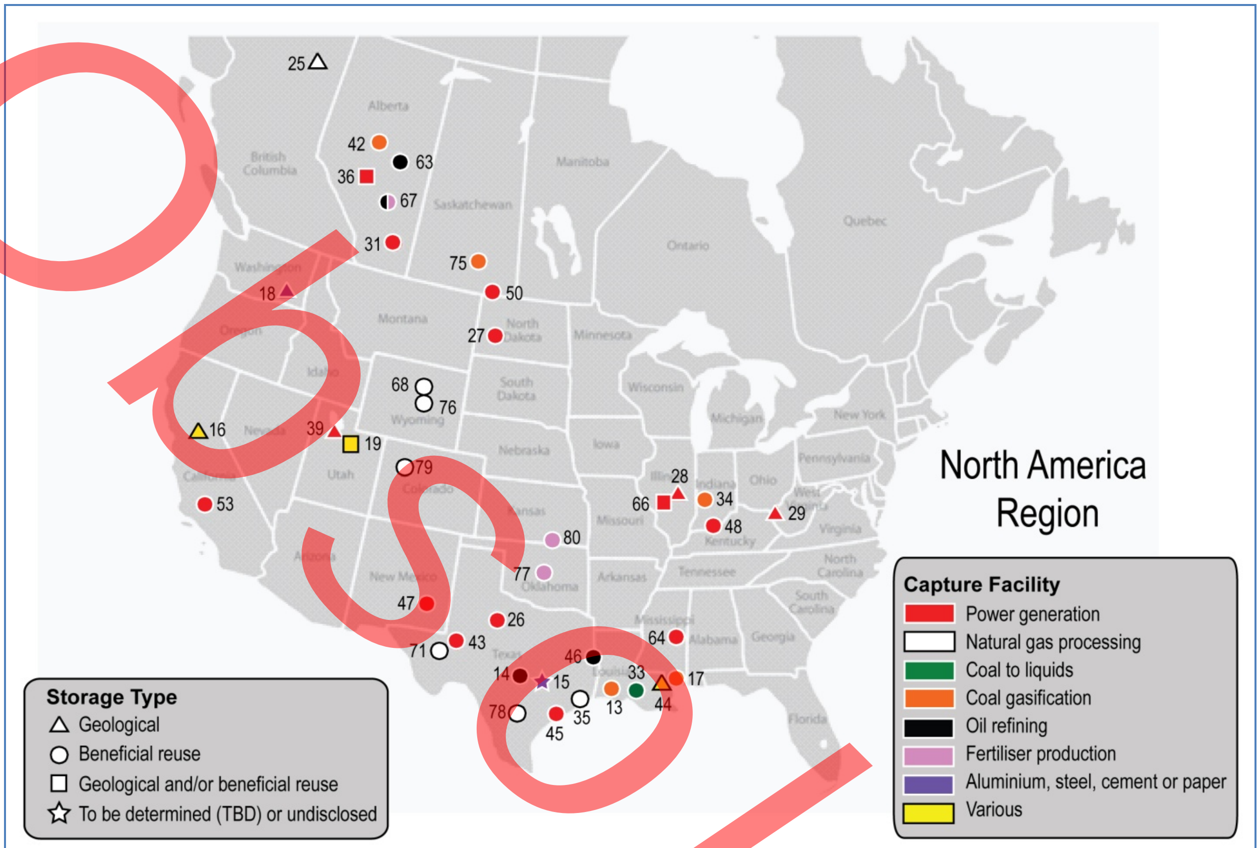


Figure 11B. Active or planned large-scale integrated projects in North America by capture facility and storage type (Source: Global CCS Institute 2010) [Note: project numbers refer to GCCSI report]

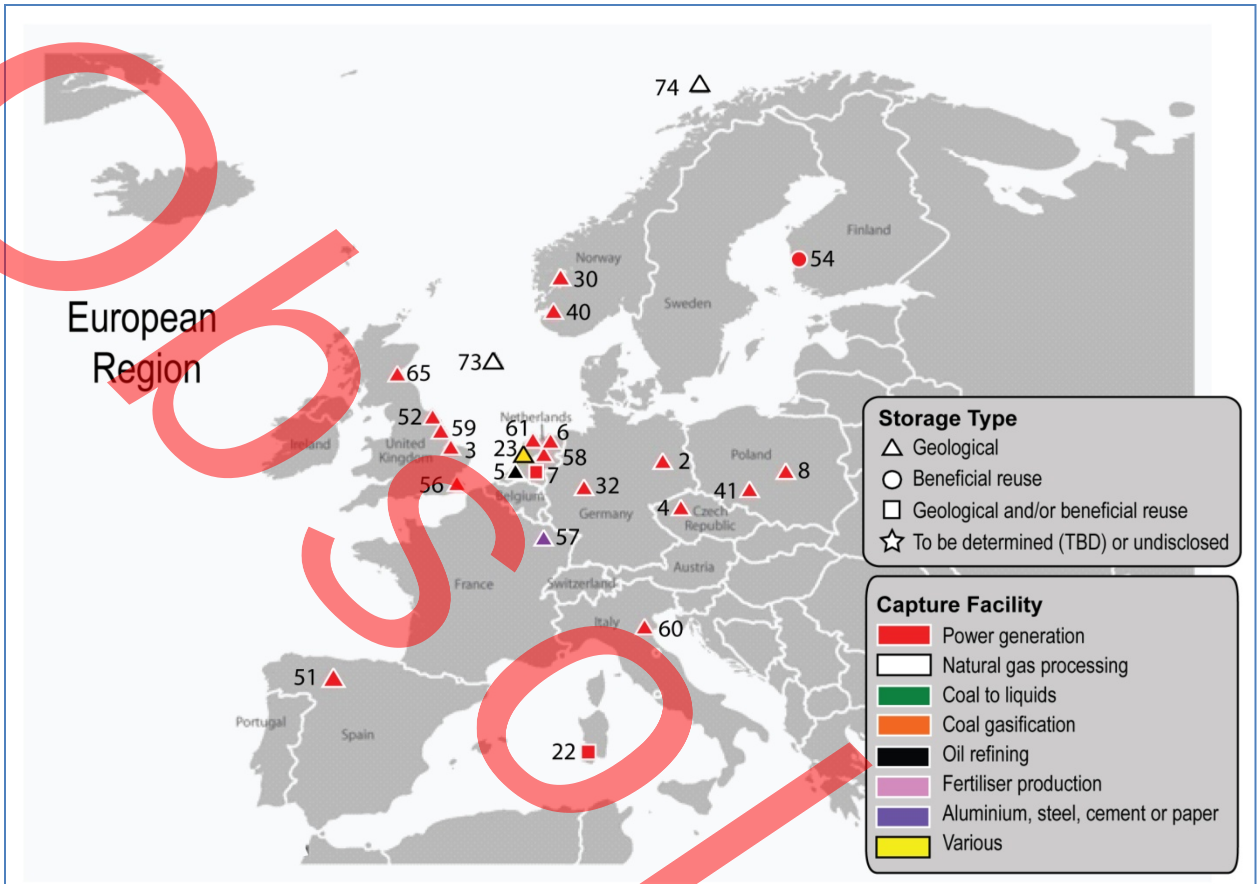


Figure 11C. Active or planned large-scale integrated projects in Europe by capture facility and storage type (Source: Global CCS Institute 2010) [Note: project numbers refer to GCCSI report]

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.

2004 CSLF TRM			
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

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 formally recognized more than 30 CCS projects, details of which are available on the CSLF website. Other CCS projects and associated details are available on IEA GHG website: http://www.ieaghg.org/ and the Global CCS Institute website: http://www.globalccsinstitute.com/.

2.3.1 Operational Commercial-scale Projects

Across the world there are several 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 is owned by Statoil and captures about 1 Mt/a of CO_2 that is removed from extracted natural gas, and immediately re-injects it 1,000 meters below the sea floor into the Utsira saline formation. In operation since 1996. Shutdown is 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 1.2 Mt/a of CO_2 captured during natural gas extraction is injected into the Krechba formation at a depth of 1,800 meters. In operation since 2004. Shutdown is 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 Statoil and captures 0.7 Mt/a of CO_2 that is transported via a 160 km pipeline for injection into the Tubåen sandstone formation 2,600 meters under the seabed. In operation since 2007. Shutdown is planned in 2035. http://www.statoil.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx
4. **Weyburn-Midale Operations** – Saskatchewan, Canada. The Weyburn Field operated by Cenovus Energy has been injecting CO_2 as part of an ongoing EOR operation since October 2000. The adjacent Midale Field, operated by Apache Canada, began CO_2 injection in 2005. Combined, about 2.8 Mt/a of CO_2 of anthropogenic CO_2 originating from the Great Plains Synfuels Plant (coal gasification) in North Dakota, USA is transported by pipeline 330 km across the Canadian border and injected into these depleting oil fields. CO_2 produced with the oil is also captured and re-injected into the reservoirs, meaning over 5 Mt/a of CO_2 is injected annually into these fields, including CO_2 recycled with CO_2 directly from the Great Plains Synfuels. Prior to the start of injection in 2000 a research project was initiated to study aspects of geological storage of CO_2 that involved collecting data from a number of baseline surveys and included studies around site characterization, geochemical and geophysical monitoring, reservoir modeling, risk assessment, and public outreach. This research, managed by the Petroleum Technology Research Centre, is currently in the Final Phase of the IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project that will be completing its ongoing activities in 2012. A summary of the first phase of work was produced in 2004 and is available at: http://www.ptrc.ca/.

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. **CO_2 capture and EOR Pilot China SINOPEC Shengli Oil Field –** Shengli Oil Field, China. This pilot scale test aims to capture CO_2 from flue gas at scale of 30,000 t/a and inject the CO_2 into an oil reservoir for EOR in low-permeability reservoirs at Shengli Oil Field. The pilot project started operation in mid-2010.
6. **Huaneng Shanghai Shidongkou Power Plant CO_2 Capture Project –** Baoshan district, Shanghai. This demonstration project is developed based on the successful 3,000 tonnes per year (t/a) pilot operation in Gaobeidian Thermal Power Plant in Beijing and is the largest coal-fired power plant post-combustion capture unit in the world. More than 100,000 t/a of CO_2 can be captured each year, 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 2010.
7. **Hechuan Shuanghuai Power Plant Carbon Capture –** Hechuan, Chongqing, China. The project plant can annually treat 50 million cubic meters (Nm^3) 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 January 2010.
8. **CO_2SINK/Ketzin CO_2 Storage Pilot –** near Berlin, Germany. This project, operated by GeoForschungs Zentrum Potsdam and finished in 2010, aimed for a better understanding of geological CO_2 storage in a saline aquifer. The main focus of the project was the development and testing of monitoring techniques. Furthermore, CO_2SINK served as a test site for CO_2 injection and safety measures. Being close to a metropolitan area, the test site provides a unique opportunity to develop a European showcase for CO_2 storage on land. The project has stored 33,000 tonnes of CO_2 over a two-year period. The work involved intensive monitoring of the fate of the injected CO_2 using a broad range of geophysical, geochemical and microbiological techniques, the development and benchmarking of numerical modeling, and the definition of risk assessment strategies, accompanied by a public outreach program. The storage site continues to be actively involved in other international research actions.
   http://www.co2sink.org/
9. **Vattenfall's Oxyfuel Pilot Plant Schwarze Pumpe –** Brandenburg, Germany. Based on an oxy-combustion concept, this pilot plant with a capacity of 30 MWth represents the complete technology chain from air separation over combustion and flue gas cleaning to CO2 separation. From the inauguration in September 2008 until mid 2011 it was operated more than 12,000 hours. In addition to a storage campaign together with CO_2Sink in Ketzin, it is also planned to use CO_2 of the pilot plant for supportive tests in the context of the Jänschwalde CCS demonstration project of Vattenfall.
   http://www.vattenfall.com/en/ccs/schwarze-pumpe_73203.htm

10. **American Electric Power (AEP) Mountaineer –** West Virginia, United States. AEP's Mountaineer plant is a 1,300 MWe 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. The demonstration project has been successful. http://sequestration.mit.edu/tools/projects/aep_alstom_mountaineer.html
11. **Total Lacq Pilot Project –** Pyrénées-Atlantique, France. This 30 MWth gas boiler project uses oxy-combustion capture technology. CO_2 is transported via an existing 30 km pipeline and stored in a very deep (4,500 meters) depleted gas field. This project will capture and store up to 120,000 tonnes of CO_2 over the two-year test period. Operational since January 2010. http://www.total.com/en/special-reports/capture-and-geological-storage-of-co2/capture-and-geological-storage-of-co2-the-lacq-demonstration-200969.html


CCS Pilot Project at Lacq, France

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. Several projects listed in the 2009 TRM were eventually cancelled, and a majority of them had to re-baseline their initial schedules. Hence, it is anticipated that some of these projects may ultimately be delayed or cancelled, potentially due to a lack of government funding, inadequate regulatory environment, community opposition, or changed economics.

12. **Callide Oxyfuel Project (Callide 'A') –** Queensland, Australia. This demonstration project will capture up to 10,000 t/a of CO_2 at a retrofitted oxyfuel 30 MWe power station. The CO_2 will be transported by truck and injected into an onshore saline formation. This project is being developed through an Australia-Japan technology alliance. The first stage is in progress with the Callide A Power Station in operation since construction started in September 2009. Full operation, including capture, is scheduled for mid-2011 followed by a two-year demonstration and R&D program. http://www.callideoxyfuel.com/What/CallideOxyfuelProject.aspx
13. The **Perdaman Gasification Project –** Western Australia, Australia. This project, which is developed as part of the Collie Hub, will produce 2.05 Mt of urea per annum using sub-bituminous coal as a feedstock. Approximately 2.5 Mt/a of sequestration-ready, high purity CO_2 will be generated as part of the urea production process. Project operation is expected in 2013-2014. http://www.perdaman.com.au/

14. The **Gorgon Carbon Dioxide Injection Project** – Western Australia, Australia. This project is an integral component of the larger Gorgon Project operated by Chevron Australia. The Gorgon Project includes the construction of a 15 Mt/a LNG plant and a domestic gas plant with the capacity to provide 300 terajoules of domestic gas per day. Between 3.4 and 4.0 Mt/a of reservoir CO_2, will be separated from the natural gas as part of the gas processing operations and transported by pipeline for injection into an onshore deep saline formation. The Final Investment Decision for the Gorgon Project was made in September 2009, with the first shipment of LNG expected in 2014. Injection of reservoir CO_2 should commence some 6 to 12 months following the first shipment of LNG.
http://www.chevronaustralia.com/ourbusinesses/gorgon.aspx
15. **Project Pioneer** – Alberta, Canada. This integrated project will capture 1 Mt/a of CO_2 from TransAlta's new supercritical Keephills 3 coal-fired power plant located in central Alberta, using a post-combustion capture technology. CO_2 will be transported to a nearby Enhanced Oil Recovery project and injected into a deep saline formation. Project operation is expected to begin in 2015.
http://alberta.ca/home/NewsFrame.cfm?ReleaseID=/acn/200810/24549060A11EE-A487-6EAB-0BA6A4955D18D734.html
16. **Quest CO_2 Capture and Storage Project** – Alberta, Canada. This project will store up to 1.2 Mt/a 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
17. **Swan Hills Synfuels Project** – Alberta, Canada, will use in-situ coal gasification to tap a coal seam at 1,400 meters depth to manufacture syngas. The syngas will be processed in a gas plant to pre-combustion capture 1.3 Mt/a of CO_2, which will be sequestered in local area EOR projects. The clean low-carbon syngas will fuel 300 MWe of high efficiency power generation. CO_2 injection is expected to begin in 2015.
http://www.swanhills-synfuels.com
18. **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 1.2-2 Mt/a of CO_2 in a nearby saline formation.
http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/19-PCOR_Fort%20Nelson%20Demonstration_PhIII.pdf
19. **GreenGen IGCC Project** – Tianjin, China. This project aims at capturing 2 Mt/a of CO_2 from a 400 MWe IGCC power plant whose generating efficiency is expected to be 48.4 percent. The project intents to be implemented in three Phases, and at the completion of Phase 3, the CO_2 captured is planned to be used for EOR in possible sites nearby. The first phase of the project is under construction and the 250 MWe IGCC

power unit is expected to be operational in 2013. The entire project is expected to be finished in 2016.
http://www.greengen.com.cn/en/aboutgreengenproject.htm

20. **Vattenfall Jänschwalde –** Brandenburg, Germany. It is planned to erect a new 250 MWe Oxyfuel block at an operational power plant site and retrofit an existing block with post-combustion capture equivalent to 50 MWe. Approximately 1.7 Mt/a of CO_2 will be captured. The future storage site has not been firmly chosen yet, and there are three possible alternatives: Birkholz and Neutrebbin (both saline aquifers) and Altmark (a natural gas field). In December 2009, Vattenfall was awarded €180 million as part of the European Energy Programme for Recovery (EEPR) for the Jänschwalde demonstration plant. Furthermore, in 2011, Vattenfall applied for funding within the European Union (EU) NER300 climate funding program. Power station operation is targeted for 2015.
http://www.vattenfall.com/en/ccs/janschwalde.htm

21. **Porto Tolle –** Rovigo, Italy. This project aims at retrofitting one of the three 660 MWe units at Enel's Porto Tolle coal power plant with CCS. The capture part will treat flue gases corresponding to 250 MWe electrical output. Up to 1 Mt/a 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. Meanwhile, the pilot plant was commissioned and the experimental phase started in June 2010. For the Porto Tolle demo plant, four licensors have been selected to develop the FEED studies for the Carbon Capture Unit; the contracts have been awarded in August 2010 and the studies will be completed in April 2011. A saline aquifer located offshore in the northern Adriatic Sea has been selected and detailed reservoir characterization studies are being carried out.
http://www.zeportotolle.com/

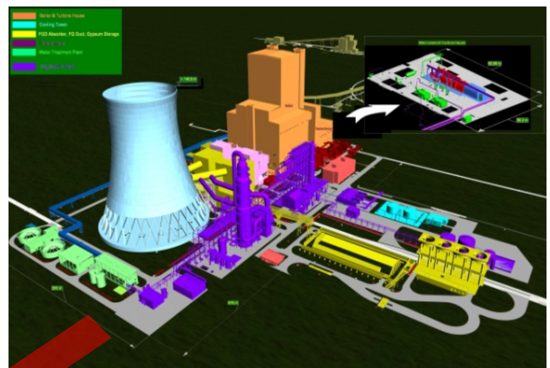
22. **Rotterdam Afvang en Opslag Demo (ROAD) –** Maasvlakte, the Netherlands. E.ON Benelux's power plant at Maasvlakte was retrofitted with a carbon capture pilot plant in 2008. A full-scale CCS project capturing up to 1.1 Mt/a of CO_2 is under development as part of the wider Rotterdam Climate Initiative (RCI). In December 2009, the European Commission committed €180 million to ROAD, while the Dutch government committed a further €150 million in May 2010. Recently, the project has tendered the capture plant; for this process, six preliminary studies and two FEED studies were conducted. In parallel, a technical transport and storage concept was selected, routing studies on the pipeline were completed and a geological field study was conducted. The ROAD project submitted its "starting note" for the Environmental Impact Assessment in 2010 and in March 2011 permit applications will be submitted. Project operation is expected to begin in 2013.
http://www.eon.com/en/businessareas/35244.jsp

23. **SEQ (ZEPP) –** IJmuiden/Velsen, The Netherlands. A 15 MWe gas-fired oxyfuel plant will be built at Tata Steel Europe's Ijmuiden steelworks. Focus is the demonstration of the viability of the process on different types of gas, including material testing, on a larger scale through prolonged test runs. Data will be used in an included FEED-study

for the next step to build a commercial 280 MWe plant. Storage of the captured CO_2 is under evaluation pending decision on the site for the 280 MWe plant .
http://www.esteem-tool.eu/fileadmin/esteem-tool/docs/ZEPP.pdf

24. **Mongstad Fullscale CCS** – Mongstad, Norway. A gas fired CHP plant at the Mongstad refinery was given a construction permit under conditions of capturing CO_2 from the flue gas (an agreement between Statoil and Norwegian government was signed in 2006). The project is under development by Statoil and Gassnova with the expected investment decision in 2016. 1 Mt/a of CO_2 is planned to be captured and stored.
http://www.statoil.com/en/TechnologyInnovation/NewEnergy/Co2Management/Pages/Mongstad.aspx

25. **Bełchatów CCS Project** – Bełchatów, Poland. An existing unit of the Bełchatów power plant will be retrofitted with a 0.1 Mt/a pilot carbon capture plant using Alstom's advanced amines technology. A full-scale 1.8 Mt/a capture plant will then be installed at an 858 MWe 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. Some delay has occurred with the storage and transport activities due to local public resistance. This delay is not expected to affect the project completion and the full chain is still foreseen to be completed in 2015 as expected.
http://microsites.ccsnetwork.eu/belchatow



Power Plant and CCP Integration, Bełchatów CCS Project

26. **CIUDEN's Test Facilities** – Compostilla, Ponferrada, Spain. This project aims at demonstrating the full CCS chain using oxyfuel and fluidized bed technology on a 30 MW pilot plant which will scale up to 320 MWe. Up to 1.1 Mt/a of CO_2 will be stored in a saline aquifer. Two potential storage sites have been identified, located in saline aquifers at a depth in excess of 800m. A 3D seismic survey and a 3D magnetotelluric acquisition for the characterization of the storage site have been undertaken. The project was awarded €180 million as part of the EEPR. The project is scheduled to be operational at 320 MWe by December 2015.
http://compostillaproject.eu/oxycfb300

27. **Don Valley Power Project (formally Hatfield)** – South Yorkshire, United Kingdom (UK). This capture-only project is developed by 2Co Power **(**Yorkshire**)** Ltd (formerly Powerfuel Power Ltd) and will capture up to 5 Mt/a of CO_2 from a 900 MWe coal-fired power station. 2Co Power 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 was originally scheduled to begin in 2014. The project completed the FEED study for the capture part and significant process was made on the storage site characterization.

28. **Masdar CCS Project** – Abu Dhabi, United Arab Emirates. Deployment planned in phases linking CO_2 capture from a steel plant (0.8 Mt/a), a conventional gas power plant (1.8 Mt/a; post-combustion), an aluminum production facility (1.7 Mt/a; post combustion) and a hydrogen power plant (1.7 Mt/a; pre-combustion), transported via a pipeline network of up to 500 km and used for EOR. The first phase of the Project is CO_2 from a steel plant (0.8 Mt/a) transported via the initial deployment of the pipeline network (50 km). Operation of the first phase is expected by 2015. Preferred post combustion capture technologies for latter implementation phases are under development.
29. **Occidental Gas Processing Plant** – Texas, United States. 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. This project is currently under construction.
30. **Hydrogen Energy California Project (HECA) IGCC –** California, United States. This 250 MWe IGCC project will burn coal and petroleum coke to produce hydrogen for power generation with low emissions of criteria pollutants while putting to beneficial reuse and permanently sequestering 90 percent of the CO_2 in an EOR application. The plant is expected to begin operation in late 2016. http://sequestration.mit.edu/tools/projects/bp_carson.html
31. **FutureGen 2.0 Project –** Illinois, United States. This project will repower Ameren's 200 MWe Unit 4 in Meredosia, Illinois with advanced oxy-combustion technology. The plant's new boiler, air separation unit, CO_2 purification and compression unit will deliver 90 percent CO_2 capture. More than one million tons of captured CO_2 per year will be transported and sequestered. The project is scheduled to be operational by late 2012.
32. **Midwest Geological Sequestration Consortium (MGSC) Illinois Basin** – Decatur Project – Illinois, United States. MGSC partners with Archer Daniels Midland (ADM) in this large-scale demonstration project where ADM's ethanol facility will capture one million tons of CO_2 over three years and store it on site in a saline formation. The project is expected to be operational in 2011. http://www.netl.doe.gov/publications/press/2009/09008CO2_Injection_Well_Drilling_Begins.html
33. **Southeast Regional Carbon Sequestration Partnership (SECARB) Plant Barry Project –** Alabama, United States. CO_2 will be injected near a power plant site in the SECARB Gulf Coast region. At least 100,000 metric tons of CO_2 per year will be injected for three years beginning in 2011. The CO_2 source will be from a newly-constructed large pilot-scale post-combustion CO_2 capture facility located at Alabama Power's Plant Barry, a coal-fired power plant located in Mobile County, Alabama. The CO_2 will be compressed and transported approximately ten miles to the injection site

located in Citronelle. http://www.netl.doe.gov/technologies/carbon_seq/infrastructure/rcsp/secarb.html

34. **Air Products & Chemicals (APCI) Port Arthur Project –** Texas, United States. In this project APCI will retrofit two steam methane reformers using a Vacuum Swing Adsorption system to concentrate the CO_2 followed by compression and drying processes. The technology will remove more than 90 percent of the CO_2 from the process gas stream, yielding approximately one million metric tons per year of CO_2, which will be delivered for sequestration and EOR. Operations will begin in 2013.

35. **Northeastern Project** – Oklahoma, United States. This project will capture CO_2 using a chilled ammonia post-combustion capture system (200 MW scale) fitted onto a 450 MWe power station. The CO_2 will be used for EOR. Operation is targeted for 2011. http://www.co2crc.com.au/demo/p_northeast.html

36. **Kemper IGCC Project –** Mississippi, United States. The Southern Company/ Mississippi Power facility is a 582 MWe IGCC plant that will gasify lignite coal and capture 65 percent of the CO_2 via Selexol. A 60-mile pipeline will be built, connecting to an existing pipeline used for EOR. The facility is expected to be operational by mid-2014.

37. **Summit Texas Clean Energy Project –** Texas, United States. This project will integrate carbon capture technology (water-gas shift and Linde Rectisol®) with Siemens IGCC, and other industrial chemicals technologies, to capture about 90 percent of the CO_2 or about 2.7 Mt/a, at a new poly-generation facility. The captured CO_2 will be compressed and delivered through an existing pipeline for beneficial use and geologic storage via EOR. Demonstration operations will commence in 2014. http://www.texascleanenergyproject.com

38. **W.A. Parish Plant (NRG Energy) CO_2 Capture and Storage Project** – Texas, United States. The project will demonstrate the ability of the Fluor Econamine FG PlusSM technology to capture 90 percent of the CO_2 emitted from a 60 MW flue gas stream. The project will demonstrate a number of recent technological advances to the Fluor Econamine FG PlusSM technology, including solvent, absorber inter-cooling, and lean solution vapor compression technologies. The captured CO_2 will be compressed and transported through a pipeline, and up to 0.4 Mt/a of CO_2 will be sequestered in geologic formations via EOR. The project is expected to be operational by 2014. http://sequestration.mit.edu/tools/projects/wa_parish.html

39. **Leucadia Energy, Port Charles Project** – Louisiana, United States. This project will capture and sequester 4.5 Mt/a of CO_2 from a new methanol plant in Lake Charles, Louisiana, United States. The CO_2 will be delivered via a 12-mile connector pipeline to an existing interstate CO_2 pipeline and sequestered via use for EOR. The project includes integration of CO_2 capture, transportation/delivery, and sequestration incorporating comprehensive monitoring, verification, and accounting. Operations will begin in late 2014.

40. The **CCS Large-scale Demonstration Project in Japan –** This project is being conducted by the Ministry of Economy, Trade and Industry of Japan. Field surveys have been carried out at some candidate fields for selecting demonstration sites.

2.3.4 CO_2 Hubs and Networks

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

41. The **CarbonNet Hub Project** supported by the state government of Victoria in Australia, aims to collect three to five Mt/a of CO_2 captured in the Latrobe Valley and transport it via pipeline for sequestration. The network has the potential to be scaled up to receive up to 20 Mt/a of CO_2. It is one of the short-listed projects to be funded under the Australian government's CCS Flagship Program and is also supported by the Global CCS Institute. http://new.dpi.vic.gov.au/energy/projects-research-development/ccs/fact-sheet-carbonnet-project
42. The **Collie South West Hub Project** supported by the Department of Mines and Petroleum in Western Australia, which initially aims to capture between 2.5 and 7.5 Mt/a of CO_2 from various industrial and power generation sources. The CO_2 would be transported 80 km by pipeline at stored 2-3 km deep in the Lesueur sandstone formations in the South Perth Basin. Project operation is expected in 2015. This hub concept has been short-listed in the Australian government's CCS Flagship Program. http://www.dmp.wa.gov.au/9514.aspx
43. 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 Mt/a of CO_2 captured from different sources in the Heartland industrial region, with a maximum pipeline capacity of over 14 Mt/a (i.e., 40,000 tonnes per day [tpd]). http://www.enhanceenergy.com/co2_pipeline/index.html
44. 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
45. 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 captures 70,000 t/a of CO_2 from a nearby ammonia plant utilizing 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/info_page/pots_rd.asp
2. **Latrobe Valley PCC project –** Victoria, Australia. A CSIRO mobile pilot PCC facility designed to capture approximately 1,000 t/a of 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 had been planned for June 2010.
http://www.csiro.au/news/CarbonDioxideCapture.html
3. **Delta Electricity Project –** The project supports a feasibility study for a medium-scale CCS project involving the retrofit of post-combustion capture technology to an existing coal-fired power station. Vales Point has been selected as the most appropriate location. This study is linked in with geological storage assessment in New South Wales (NSW), a NSW Government Initiative. The Delta Electricity Project builds upon a pilot scale CCS project by Delta at the Munmorah Power Station.
http://www.de.com.au/Sustainability/Greenhouse/Carbon-Capture-Research-Project/Carbon-Capture-Research-Project/default.aspx
4. **CO2CRC Otway Project Stage 1 & 2 –** Victoria, Australia. During Stage 1 of the project (in 2008 and 2009), approximately 60,000 tons of CO_2 was injected into a depleted gas field at approximately 2,000 meters depth. This first stage of the project tested modeling prediction, capacity estimation, containment and monitoring technologies. An additional injection well was also implemented for residual trapping and saline formation testing. Larger scale injection for Stage 2 of the project started in 2011. Monitoring of Stage 1 will continue to 2013 or later.
http://www.co2crc.com.au/
5. **CO2CRC 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 2009. The results will be known in 2011.
http://www.co2crc.com.au/dls/brochures/CO2CRC_H3_brochure_A4.pdf
6. **CO2CRC Mulgrave HRL –** Victoria Australia. The research program at Mulgrave aims at assessing and optimizing 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; optimizing operating parameters; developing engineering solutions; assessing energy integration options; reviewing technical and economic viability for commercial use. Tests started in 2009. The results will be known in 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. The project aims to demonstrate PCC at small scale (approximately 1,000 t/a of CO_2) using liquid absorbent capture process, while testing alternative operating regimes to reduce the energy penalty and additional resource requirements. The pilot plant's construction was completed in early 2010 and became operational in March 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 started in 2010. Shutdown planned for January 2015.
http://www.GreenMagGroup.com

China

9. **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 un-mineable deep coal seams. The project is based on previous cooperative projects between the Chinese and Canadian governments (2002-2007). By May 2010, the project had met its goal of 240 tonnes CO_2 injection. Operation of the test is ongoing.

10. **Microalgae Bio-Energy and Carbon Sequestration Project** – Dalate, Inner Mongolia. Based on successful lab scale pilot, this project will use microalgae to absorb CO_2 emitted from the flue gas of a coal-derived methanol and coal derived dimethyl ether production equipment and produce bio-diesel as well as feeds. The planned absorption capacity will be 320,000 tons of CO_2 annually. The project began in May 2010 and will be completed in two to three years.

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 using CO_2 as a raw material. The CO_2 is captured from ethanol plants and total amount of CO_2 utilized is about 8,000 t/a. Operational, with expansion lines planned through 2016.

12. **Shenhua Group CCS Demonstration Project –** Erdos, Inner Mongolia. Studies have shown that the underground area 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 t/a of CO_2. 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, and test injection began in 2010.

Europe

13. **ENEL CCS1 – Post-combustion Pilot Capture Unit** – Brindisi, Italy. A first post-combustion capture project involves the construction of a pilot installation of 10,000 Nm^3/h at the Brindisi Sud coal power plant. The CO_2 produced will be stored by ENI at the Cortemaggiore site. A 0.8-MNm^3/h installation will then be constructed to treat part of the flue gases of a 660 MWe unit of the Porto Tolle power plant. http://www.enel.com/en/research/carbon/
14. **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 was to start in October 2010. http://www.cslforum.org/meetings/berlin2005/index.html
15. **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 MWe demonstration unit. http://www.iteaspa.it/technologies.asp
16. **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.
17. **CO_2 Field Lab** – Svelvik, Norway. SINTEF is project leader for this CO_2 storage pilot at Svelvik, south of Oslo, Norway, where the main objective is to assure and increase CO_2 storage safety by obtaining valuable knowledge about monitoring of CO_2 migration in geological formations. This will enable detection of possible CO_2 leakage at the earliest possible stage. http://www.sintef.no/Projectweb/co2fieldlab/
18. **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 inlate 2011 or early 2012. The project is owned by the Norwegian State (represented by Gassnova SF), Statoil, Shell, and Sasol and will have an annual capacity

The Technology Centre Mongstad (TCM)

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 will be possible to add other technologies later on.
http://www.tcmda.no/

19. **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

20. **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 optimize integration. ELCOGAS power plant in Puertollano will be retrofitted with a 14 MWth pilot plant capturing 100 tpd of CO_2. Operation is expected in Q2 2010.
http://www.elcogas.es/

21. **Ferrybridge CCS Trials** – West Yorkshire, UK. 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

22. **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 tons.
http://www.euroinvestor.co.uk/news/story.aspx?id=10986316

23. **Longyearbyen CO_2 Lab** – Svalbard, Norway. The University Centre in Svalbard (UNIS) has taken the initiative to establish a CO_2 storage laboratory at Svalbard. An aquifer

suitable for CO_2 storage has been identified, and injectivity was verified during extensive testing in 2010. Injection of CO_2 at pilot scale is expected to start in 2012.
http://co2-ccs.unis.no/

24. **CO_2 Field Lab –** Svelvik , Norway. SINTEF is project leader for this CO_2 storage pilot at Svelvik, south of Oslo, Norway, where the main objective is to assure and increase CO_2 storage safety by obtaining valuable knowledge about monitoring of CO_2 migration in geological formations. This will enable detection of possible CO_2 leakage at the earliest possible stage.
http://www.sintef.no/Projectweb/co2fieldlab/

25. **ENI – Feasibility Study and Pilot Project of Injection into a Depleted Hydrocarbon Field.** ENI has run various studies and preliminary evaluations as part of the design of surface infrastructure for CO_2 injection and monitoring in the Cortemaggiore field (Piacenza). ENI has also analyzed the legal and social aspects linked to the storage. The injection of 8,000 t/a CO_2 will follow over a three-year period, followed by two years of post injection monitoring. Studies on the utilization of the CO_2 will also be run in order to increase the recovery factor from Italian hydrocarbon fields.

26. **CARBOSULCIS – Methane Recovery and CO_2 Storage in the Sulcis Coal Basin –** Sardinia Island, Italy. The project has the objective of evaluating the feasibility of methane recovery (CBM) and of CO_2 storage (ECBM) in vast parts of the Sulcis coal basin, in South-West Sardinia, which are not suitable for mining activities. Once the characterization of the basin has been completed through studies, analyses of existing data and experimentation, the second stage will follow, with the aim of defining all the remaining aspects for the construction of a pilot injection and storage installation.
http://www.zeroemission.enea.it/risorse-en-en/carbosulcis-progetto-stoccaggio-co2

Japan

27. **Mikawa PCC Pilot Plant** – Fukuoka Prefecture, Japan. This facility is being utilized to improve and verify performance, operability, and maintainability of PCC technology at a pilot plant using live flue gas slipstream of a coal fired thermal power plant. It collects ten tons of CO_2 per day at more than 90 percent capture rate. Operational since August 2009.
http://www.toshiba.co.jp/about/press/2008_12/pr0301.htm

North America

28. **SECARB Cranfield Early Injection (Phase III) Test –** Mississippi, United States. This project has injected over two million tons of CO_2 into the saline portion of an oil-bearing formation. This large volume injection into the Tuscaloosa formation provides an early opportunity to assess monitoring and modeling approaches.

29. **PCOR Bell Creek (Phase III) Project –** Montana, United States. 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.
http://www.netl.doe.gov/technologies/carbon_seq/partnerships/development-phase.html

30. **Big Sky Carbon Sequestration Partnership Basalt Field Validation (Phase II) Test –** Washington, United States. 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.
http://www.netl.doe.gov/technologies/carbon_seq/core_rd/RegionalPartnership/BIGSKY-VP.html

31. **Big Sky Carbon Sequestration Partnership (Phase III) Kevin Dome Project –** Montana, United States. This proposed project will assess the potential of the Kevin Dome as a geologic storage site. Assessing Kevin Dome will be beneficial for other carbon storage projects because Kevin Dome is similar to several other domes in the Big Sky region.
http://www.bigskyco2.org/research/geologic/kevincharacterization

32. **Southwest Partnership Gordon Creek (Phase III) –** Utah, United States. Objectives of this project include: estimate capacity of the Jurassic Saline reservoirs, estimate seal efficiency, and assess new monitoring methods.
http://www.southwestcarbonpartnership.org

33. **Midwest Regional Carbon Sequestration Partnership Michigan Basin (Phase II) Geological Test Site –** Michigan, United States. 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.
http://www.netl.doe.gov/technologies/carbon_seq/core_rd/RegionalPartnership/MRCSP-VP.html

34. **Midwest Regional Carbon Sequestration Partnership (Phase III) Michigan Basin Test –** Michigan, United States. The proposed site is located on a state-owned, military land management area in Otsego County, approximately ten miles from the site of the earlier Phase II project. For this next phase, the primary carbon dioxide storage formation would be the St. Peter Sandstone at a depth of about 7,500 feet underground, below natural gas and oil producing zones. Subsequent activities include obtaining an injection permit, four years of carbon dioxide injection and a further four years of monitoring after injection is completed.
http://216.109.210.162/MichiganBasin_development.aspx

35. **PCOR Northwest McGregor EOR Project in the Williston Basin –** North Dakota, United States. The project evaluates the potential of "huff'n'puff" technology 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/publications/factsheets/project/Project687_8P.pdf

36. **Southwest Partnership Aneth Enhanced Oil Recovery, Sequestration Test G1 –** Utah, United States. 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

37. **SECARB Black Warrior Basin Coal Seam Project –** Alabama, United States. Objectives for this project are to determine if sequestration of CO_2 in mature coal bed methane reservoirs is a safe and effective method to mitigate GHG emissions; and to determine if sufficient injectivity exists to drive CO_2-enhanced coal bed methane recovery. Operational since September 2009.
http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/1-SECARB_Black%20Warrior%20Basin_Coal.pdf

38. **West Coast Regional Carbon Sequestration Partnership (WESTCARB) Arizona Utilities CO_2 Storage Pilot –** Arizona, United States. This pilot test conducted well drilling, characterization, and analysis to assess the potential of the Colorado Plateau for geologic storage of CO_2.
http://www.westcarb.org/AZ_pilot_cholla.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 the following:

2.5.1 International Government and Non-Government Initiatives

1. **The IEA Greenhouse Gas R&D Programme (IEA GHG)**, 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 CCS Institute (GCCSI)** was formally launched in April 2009 by the Australian Government to accelerate the deployment of CCS technology globally. By fostering cooperation on CCS projects and technologies and facilitating the sharing of information, the GCCSI is playing a key role in achieving the G8 goal of the broad deployment of CCS technology by 2020. The GCCSI is a member-based international

organization, and now has over 300 members, covering governments, companies and organizations that support and demonstrate a legitimate interest in accelerating the commercial deployment of CCS. Total Australian Government funding, expended or committed, for the GCCSI stands at A$305 million out to at least 2015-2016.

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 MWe 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 United Kingdom 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 National CO_2 Infrastructure Plan** was announced by the Australian government in the 2011-2012 Budget. The government will provide A$60.9 million in funding over four years to establish a National CO_2 Infrastructure Plan. The Plan includes a storage exploration and appraisal program for the identification of long-term storage hubs, acquisition of pre-competitive offshore and onshore CO_2 storage data, a national CO_2 drilling rig deployment strategy, and an infrastructure and transport assessment.
9. **The United States Interagency Task Force on Carbon Capture and Storage** was established to propose a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within ten years to address the Presidential goal of bringing five to ten commercial demonstration projects online by 2016. Its primary role was to formally address possible incentives for CCS adoption and any financial, economic, technological, legal, institutional, or other barriers to deployment. It also outlined how to best coordinate existing federal authorities and programs, as well as identify areas where additional federal authority may be necessary. The Interagency Task Force delivered a series of recommendations to the President on overcoming the barriers to the widespread, cost-effective deployment of CCS within ten years on August 12, 2010.

10. **The United States Department of Energy (USDOE) sponsored Regional Carbon Sequestration Partnerships (RCSP)**, which together encompass 43 states and 3 provinces of Canada, are each conducting large-scale CO_2 injection tests (up to one million tonnes 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.
    http://www.fe.doe.gov
11. **The USDOE Carbon Capture and Sequestration Simulation Initiative (CCSI)**, which includes both the CCSI and the National Risk Assessment Partnership (NRAP). These initiatives bring the breadth of USDOE modeling capabilities (represented at several national labs) in partnership with academic and industrial institutions to develop a comprehensive suite of science-based predictive models for carbon capture and sequestration technologies. CCSI focuses on accelerating the time to deployment for advanced capture technology (while reducing its capital and operating cost) by reducing or even avoiding costly intermediate-scale testing. NRAP focuses on science-based prediction of storage site performance as related to quantifying long-term liability.
12. **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.
13. **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.
14. **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 MWth pilot-scale oxy-fuel vertical combustor, entrained flow gasifier (1,500 kilopascals and 1,650°C) that is capable of operating with dry or slurry feed and a 1 MWth circulating fluidized-bed combustion (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://canmetenergycanmetenergie.nrcanrncan.gc.ca/eng/clean_fossils_fuels/carbon_capture_storage.html
15. **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 for a location in Alberta where field-

based research on CCS MMV will be undertaken. The final site was expected to be selected by the end of May 2011.

16. **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 one-ton and four-ton pilot plants, the larger hooked up to both a coal-fired electrical station as well as a gas turbine.
www.co2-research.ca/

17. **The Petroleum Technology Research Centre (PTRC)** at the University of Regina (in Regina, Canada) continues to study aspects of CO_2-EOR involving storage and in less conventional settings including heavy oil reservoirs. PTRC manages the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project, which is among the largest such projects investigating CO_2 storage in a depleting oil reservoir in the world. In addition the PTRC is managing the Aquistore Project that involves a program to capture, transport and store CO_2 in a deep saline formation in the Williston Basin.
www.ptrc.ca

18. **Oxy-combustion for Coal Fired Power Installations.** This European project, which 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, with exhaust gas recirculation and utilizing the so-called "flameless combustion".

19. **Development of Membranes for the Separation of Hydrogen from Syngas.** The main goal in this European project 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.

20. **Degradation of a Turbogas Running on Hydrogen Rich Syngas.** For this European project, analyses and modeling are being 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.

21. **Sorbent Solids Suitable for the Capture from Combustion Fumes.** For this European project, a CO_2 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.

22. **Innovative Technologies for the Improvement of the Environmental Performance of Powdered Coal Power Plants.** Activities in this European research program are in two main areas: 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.

23. **MILD Combustion Project.** The main goal of this European project is to develop and test moderate or intense low-oxygen dilution (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 MWth pilot installation coal oxyfiring with CO_2 capture is ongoing.
24. **Korea CCS Association (KCCSA)** was established (supported by the Ministry of Knowledge Economy) as an association of which members represent power and industrial sectors including oil, iron and steel, heavy industries, and engineering and construction. Also, more than 30 research institutes and universities joined the KCCSA as special members. The current activities are included in the works on the regulatory/policy system, knowledge sharing, international CCS collaboration and improving public acceptance.

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; finalization of legislation and regulations for CO_2 storage; and various state, federal, and international programs and funds to accelerate CCS deployment.

The Australian Federal Government, as well as the State governments of Queensland, Victoria, and South Australia, have passed legislation and regulations enabling the geological storage of CO_2, both offshore and onshore Australia. Legislation is being developed by New South Wales and Western Australia for those states' onshore areas. The Gillard Labor Government announced that all new coal-fired stations will be required to meet best practice emissions standards, and be Carbon Capture and Storage-ready. In early 2011, the Federal Government has proposed a carbon price mechanism, which will commence with a fixed price on GHG emissions for three to five years before converting to a cap-and-trade emissions trading scheme. The carbon price mechanism could commence as early as July 2012, although it must first be agreed with a majority in both houses of Parliament and pass legislation.

Australian Federal and State Governments commitments to CCS include:

- A total of A$305 million from 2008 to 2009 out to at least 2015-16 was committed to the GCCSI. The GCCSI was launched in April 2009 to accelerate the deployment of commercial scale CCS projects worldwide.
- Approximately A$110 million in funding allocated to the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) to support its activities through 2015. CO2CRC develops and manages a collaborative partnership between industry, government and university partners and is one of the world's leading collaborative research institutions specializing in CCS. Since 1998, the CO2CRC has undertaken

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

- Release of off-shore and onshore areas for exploration for GHG storage formations. In March 2009, the Federal Government released the first 10 off-shore areas ever offered for commercial geological GHG storage. The Victorian Government released two onshore areas in October 2009 and 13 onshore areas were released in Queensland in May 2010.
- The Federal Government's CCS Flagships program forms part of the Government's Clean Energy Initiative. It aims to support the construction of commercial scale CCS projects with an electricity generating capacity of 1,000 MWe or equivalent size for other industrial processes. Funds available under the Flagships program have been reduced from A$1.9 billion to A$1.68 billion in May 2011.
- A portion of the savings from the cuts to the CCS Flagships program has been redirected to support the creation of the A$60.9 million National CO_2 Infrastructure Plan, which aims at exploring potential storage areas and acquiring CO_2 storage data nationally.
- The Australian Government has committed A$75 million to a National Low Emissions Coal Research Program under the National Low Emissions Coal Initiative. The Government's commitment has been matched by the coal producers. The National Low Emissions Coal Council (NLECC) was tasked by the Government to develop the national research program and to establish a national research centre to implement the program.
- The Australian National Low Emissions Coal Research and Development Ltd (ANLEC R&D) was established as an independent company in March 2009. ANLEC R&D's Research Program was approved by NLECC and endorsed by the Minister for Resources and Energy in April 2010. http://www.anlecrd.com.au
- A$165 million of Federal Government support for programs, including the Carbon Storage Taskforce to produce the National Carbon Mapping & Infrastructure Plan, National Coal Research Program, Carbon Storage Initiative and other studies, plus funding for international partnership programs such as the Asia Pacific Partnership on Clean Development and Climate.
- The progress made by the National Low Emissions Coal Council and the Carbon Storage Taskforce will be further progressed by the newly formed National CCS Council, which comprises members drawn from the generation, coal and petroleum sectors.
- As part of the Australian Greens and Australian Labor Party Agreement, signed on 1 September 2010, the two political parties agreed to form a well resourced Multi-Party Climate Change Committee.

Canada

Drilling at the Fort Nelson CCS Project in winter.

In the last three years, Canada's federal and provincial governments have committed more than C$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 [Pioneer, Quest, Swan Hills Synfuels, and Alberta Carbon Trunk Line (ACTL)] in Alberta that have received provincial funding of about C$2 billion in total. Descriptions of these four projects are 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 to assess the economic and technical feasibility for CCS both onshore and offshore in Nova Scotia. Initial geological screening assessment, studies on capture technology options and the development of onshore legal/regulatory and risk management roadmaps for the province are currently near completion. The development of a public stakeholder awareness plan is also nearing completion. Looking forward, geological investigations scheduled for completion in the fall of 2011 are aimed at identifying a prospective storage site for characterization. The next phase of the capture technology assessment will be further developed into a Front End Engineering Design (FEED) document in preparation for detail design. This phase will be completed by spring of 2012. Once a project is defined, implementation of legal/regulatory and risk management roadmaps will commence. This is expected after the fall of 2012 and will be dependent on the findings of the geological investigations.

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 aims to eliminate international "fault lines" and ensure compatible estimates of reservoir capacities. The project is on target to deliver the first version of the atlas (both as web-based and print versions) by the middle of 2012.

China

Guided and supported by Chinese government, Chinese enterprises and research institutions have conducted research covering the whole CCUS technology chain and main technology directions in past years. The Chinese government, especially the Ministry of Science and Technology, is planning to increase funding on CCUS technology Research and Development, and demonstration in the 12^{th} five-year-plan period (2011-2015).

- During the 11^{th} five-year-plan period (2006-2010), China's National High-tech R&D Program (863) had supported several CCUS R&D projects, covering Post-combustion + CCS, IGCC+CCS; CO_2-Microalgea-bio diesel conversion; CO_2 mineralization, etc.; China's National Basic Research Programme (973) had supported theoretical research and pilot study on enhanced oil recovery (EOR) and CO_2 capture.
- In 2011, China's National Key Technology R&D Programme has started to fund two additional CCUS technology demonstration projects, including the 35MWth Oxy-fuel CCS demonstration and the Shenhua 10,000 t/a CO_2 storage demonstration; China's National Basic Research Programme (973) continued its support on theoretical research and pilot study on EOR.
- In 2010, Chinese Geological Survey started a CO_2 Geological Storage Capability Assessment and Demonstration in China to assess the overall geological storage potential of CO_2 in China.
- In 2011, with support from the Ministry of Science and Technology, the Administrative Centre for China's Agenda 21 led the draft CCUS Technology Development Roadmap in China;
- Initiated in 2010, some Chinese companies and research institutions are preparing to establish a cross sector cooperation platform called China Strategic Alliance on CCUS Technology Innovation. Expected to be established within 2011.

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), http://www.geus.dk/co2, are involved in several international projects on CCS. In the CO_2 Enhanced Separation and Recovery (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 also supports the IEA GHG, and thus supports the CCS activities in this program.

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 of CCS, such as geological storage pilots and development of next generation CCS technologies.

In the revised Emission Trading System (EU ETS) directive, adopted by Parliament and Council in December 2008, 300 million allowances have been set aside from the so-called "New Entrants Reserve," until 2015, for the support of large-scale demonstration projects in the areas of CCS and innovative renewables (NER300). This is a substantial fund for demonstration of low-carbon power – at the moment worth about €4.5 billion Euro – which will be used to establish public-private partnerships, with 50 percent funding of extra costs from NER and EEPR (see below) combined, and the remainder coming from project owners and Member States. Award decisions are to be taken in the second half of 2012. http://ec.europa.eu/clima/policies/lowcarbon/ner300_en.htm

In addition, the "recovery package" (European Energy Programme for recovery, EEPR) approved by the Commission in July 2009 grants €1.5 billion to support 15 CCS and off-shore wind demonstration projects in seven Member States. The six selected CCS projects are: Jänschwalde (maximum contribution of €180million), Porto Tolle (€100million), Rotterdam (€180million), Bełchatów (€180million), Compostilla (€180million), and Don Valley Power Project (formerly Hatfield) (€180million). http://ec.europa.eu/energy/eepr/index_en.htm

The European CCS Demonstration Project Network has been established to support first-mover CCS demonstration projects, particularly on issues which represent common challenges. The network allows early movers to exchange information and experience, to maximize their impact on further R&D and policy making, and to optimize costs through shared collective actions. The first projects to populate the knowledge-sharing network are the six demonstration projects co-

funded under the EEPR (see above).
http://www.ccsnetwork.eu/index.php

The EU 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 has been published in April 2011.
http://ec.europa.eu/clima/policies/lowcarbon/ccs_implementation_en.htm

France

France actively supports the development and deployment of CCS as a complementary solution in order to accelerate the reduction of CO_2 emissions and has a strong track record on R&D issues. The two main sources of public funds to foster R&D projects on CCS are managed by ANR (the French National Research Agency) and ADEME (the French Environment and Energy Management Agency).

Between 2005 and 2008, ANR supported 33 research projects for a total amount of more than €27.5 million. Among these 33 projects:

- 13 were dedicated to capture and among these, 8 have integrated transport;
- 17 were dedicated to storage whilst 12 integrated the monitoring;
- 1 is dedicated to transport;
- 1 is dedicated to risk management and safety criteria; and
- 1 concerned a socio-economic study and public awareness.

Within the 2010 program on energy efficiency and CO_2 emissions reduction in industrial systems, ANR selected projects on capture and utilization of CO_2. Further funding of carbon capture, transport, utilization, and storage projects within the upcoming ANR programs is currently under scrutiny.

The ADEME supports initiatives concerning CO_2 capture and storage and devotes special attention to energy efficiency, socioeconomic issues, and environmental impacts. Between 2001 and 2009, ADEME invested €3.7 million to support R&D projects. Among these 26 projects, 11 are dedicated to capture, one to transport, six to storage, six to techno-economic studies and two to risk management.

The conclusions of the "Grenelle de l'Environnement" in December 2007 led to a proposal to create dedicated "demo funds." During 2010, four projects are supported for a total amount of €45 million: one for storage, two for capture, one for an integrated project dedicated to reduce the emissions of the steel industry. 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.

Moreover, in the beginning of 2010, the French government decided to put in place a new policy approach on "Green Industries." Carbon capture, transport, utilization and storage (CCUS) are part of this strategy which has the main objective to develop and structure the industries of the "green economy" through ambitious industrial policy targets and actions bringing together the different stakeholders.

The initiative is coupled with a strong R&D support program. CCUS is eligible for both the creation of "Excellence institutes for low-carbon energy" (€1 billion fund managed by ANR) and demonstrators and test sites for carbon-free energy and green chemistry (€1.35 billion fund managed by ADEME).

Germany

Germany is committed to explore the technological option of CCS. Taking a long-term view, this is of particular interest in energy-intensive industrial sectors (e.g. steel, lime, cement, chemicals, or refineries) and in fossil fuelled power plants (lignite and hard coal). Through technological developments and innovation the prerequisites will be created for making electricity production from fossil energy sources, e.g. domestic lignite, climate-neutral in future. In addition to national RD&D programs in that field Germany will also be committed to European and international RD&D activities with a priority on the European Strategic Energy Technology Plan (SET-Plan).

The CO_2 Reduction Technologies (COORETEC) program of the Federal Ministry of Economics and Technology is part of the energy research program 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, CO_2 capture is a major topic. Collaborative research projects between science and industry are in the focus of the COORETEC program. In the period 2004 through 2010, nearly 340 projects, with an amount of more than €180 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 toward 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 law designed to provide a framework for the development of CCS pilot and research projects in Germany, written through a partnership between the German Minister for Economy and Minister for Environment, was approved by cabinet in April 2011 and submitted to the German Parliament. Pilot CCS projects will need to apply for approval by the end of 2016 and will not be able to store more than 3 Mt/a of CO_2 each, while the country's overall yearly storage amount of CO_2 will be capped at 8 Mt/a. The revised draft law gives the German Federal States (Bundesländer) a stronger voice with regard to the designation of the areas for the CO_2 storage demonstration projects and gives greater consideration to protecting other uses of the underground. The framework introduced in the draft bill 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 organizations and European Committees, such as in the United Nations, Committee of Energy of European Committee, International Energy Agency, and Carbon Sequestration Leadership Forum, the European Technology Platform for Zero Emissions Power Plants (ETP ZEPP), etc.

The Ministry of Environment, as the main authority responsible to coordinate the CCS Directive transposition, established a Working Group which involves representatives of research organizations and universities.

Technology providers, private energy companies and other industrial players have at times expressed an interest in CCS, but this interest has yet to culminate into a concrete project. What is more, Aegean Energy the current operator of Prinos, an off-shore mature oil field near Kavala, has indicated that this reservoir has all necessary characteristics to accommodate the injection of CO_2 under a CCS project.

PPC, which currently operates most large energy emission points within Greece, has an ambiguous stance regarding the application of CCS. Although the company is following all technological developments, it has published no concrete plans regarding the application of CCS in one of its current or projected units and has not indicated an intention to be part of any project foreseeing the application of CCS in one of its units.

The Minister of Environment has commented in a press conference that the solution of CCS application is a hard endeavour, ‘especially for a seismogenous country as Greece’ adding that it would be a mistake ‘if we merely store emissions thus perpetuating the same developmental model (http://news.pathfinder.gr/greece/news/643606.html).

Reference: Bellona report: “A Bridge to a Greener Greece: A Realistic Assessment of CCS Potential,” 2010

Italy

OGS (National Institute of Oceanography and Experimental Geophysics) is the main Italian research institution participating in a number of CCS projects of the EU Framework Programmes, including CASTOR (CO_2 from CApture to STORage), INCA-CO_2 (INternational Co-operation Actions on CO_2 capture and storage), GeoCapacity (Assessing European capacity for geological storage of carbon dioxide), CO_2 GeoNet (The European Network of eExcellence on the geological storage of CO_2), CO_2ReMoVe (CO_2 geological storage: Research Into Monitoring And Verification technology), RISCS (Research into Impacts and Safety in CO_2 Storage), CO_2CARE (Research into Impacts and Safety in CO_2 Storage), SiteChar (Characterisation of European CO_2 Storage), CGS Europe (Pan-European coordination action on CO_2 Geological Storage) and ECO_2 (Sub-seabed CO_2 Storage: Impact on Marine Ecosystems), many of which together with LA Sapienza, University of Rome.

OGS and ENEA are members of ECCSEL (European Carbon dioxide Capture and Storage Laboratory Infrastructure) and, together with a number of Italian institutes and universities, they contribute to the Joint Research Programme on CCS of EERA (European Energy Research Alliance).

The Ministry of University and Research and the Ministry of Economic Development have supported a series of initiatives on CCS. Among those not mentioned in the previous chapters, worthy to be mentioned are:

RSE – Characterization of CO_2 storage sites. The project has the objectives of pinpointing areas potentially suitable to CO_2 geological storage, creating a Geographic Information System for the National Inventory of Potential Storage Sites, refining calculation systems and tuning up instrumentation. The project involves also the monitoring of marine sites and activities favouring communication and outreach of the CCS technology.

Japan

R&D activities on CCS, which included various storage options (i.e., ocean storage, Enhanced Coal Bed Methane [ECBM], and geological storage), started in late 1980s.

From July 2003 to January 2005, 10,400 tonnes of CO_2 were injected into saline aquifer 1,000 meters below the ground surface of Iwanohara, Nagaoka site, Niigata Prefecture. Even after the end of injection, RITE continues various on-site measurements of wells to grasp CO_2 behavior underground and confirms CO_2 is safely stored. Among many demonstration projects worldwide, only Nagaoka project keeps monitoring CO_2 behavior even after the end of injection and for that reason, its monitoring results have drawn attention from all over the world.

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.

A new guideline: "For safe operation of a CCS demonstration project" was presented by the Ministry of Economy, Trade and Industry (METI) in August 2009. This guideline is a standard desired to be followed from the safety and environmental viewpoints in implementing a large-scale CCS demonstration project and is not a preliminary safety to be set up when putting CCS into practice in the future.

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

In the last ten years (2000 to 2009), Korean government has spent about US$89 million (106.9 billion Korean won) in funding for CCS R&D. Most (approx. 80 percent) of these funds have supported several independent projects to develop CO_2 capture technologies.

In April 2010, the Basic Law on Low-Carbon Green Growth went into force, which would provide a broad framework for sustainability policies in Korea. The new legislation will provide a foundation for a system for regulating GHG emission volumes and trading emission permits and will support for CCS.

In July 2010 the presidential committee on green growth (PCGG) with five ministries (MEST, MKE, MLTM, ME, and MOSF)[1] announced the national CCS master action plan. The key categories of action include: 1) innovative CCS technology development and large-scale integrated demonstrations; 2) infrastructure for CO_2 transportation; 3) selection of potential storage site and development of key storage technologies; and 4) CO_2 utilization.

The PCGG also announced that a total of US$1.9 billion will be invested to CCS next ten years (government share 52 percent, private share 48 percent). The Korea Electric Power Corp. (KEPCO), with its subsidiaries (five fossil-fuel power companies), has also committed US$1.1 billion in funding for CCS next ten years. KEPCO, state-run utility, is currently leading investment on CCS. Other major industries currently invest a small, but significant, portion and are willing to invest more.

- MKE, with 84 percent fund share (US$1.6 billion), supports the CCS technology development and demonstration including a goal of bringing two large scale integrated CCS demonstrations online by 2014 and 2016. MKE through KETEP www.ketep.re.kr has supported the technology developments for post-combustion, pre-combustion and oxy-fuel combustion including chemical looping combustion since 2006. This year MKE

[1] MEST: Ministry of Education, Science and Technology, MKE: Ministry of Knowledge Economy, MLTM: Ministry of Lands, Transportation and Maritime Affairs, ME: Ministry of Economy, MOSF: Ministry of Strategy and Finance

awarded KEPCO Research Institute three ongoing projects with government (50 percent) and private(50 percent) funding: two post-combustions and one oxy-fuel combustion:

- 10 MW pilot plant at Hadong coal-fired power plant with dry regenerable sorbent technology (US$36.6 M, 2010-2014); Scale-up from the 0.5 MW project of CDRS program (MEST, 2002-2011).
- 10 MW pilot plant at Boryeong coal-fired power plant with advanced amine (US$38.5 M, 2010-2014); scale-up from 0.1 MW test-bed at same site.
- FEED study of 100 MWe Oxy-PF demo project for repowering Youngdong Power Plant starting from 2013 (US$13.3 M, 2011-2012).

- MEST is responsible for administering the 10 year Carbon Dioxide Reduction & Sequestration (CDRS) program established in 2002 (http://www.cdrs.re.kr). The 3rd phase of the CDRS program was launched in March 2008 with a budget of US$20 M 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 oxy-fuel combustion. Dry sorbent CO_2 capture technology for post-combustion developed by KIER and KEPRI has shown excellent performance in a 25 kilowatt fluidized bed CO_2 capture process and is currently being operating 0.5 MW plant, slip-streamed from 500 MWe Hadong coal-fired Power Plant (70 to 85 percent removal performance as of August 2010).

MEST with 10 percent funding share (US$200 million) will launch new program “Korea CCS 2020 project” over nine years from 2011 to 2019.

- MLTM and ME with six percent fund share (US$120 million) focus on risk management, legal and regulatory, and public acceptance.
- The MLTM supports the program of the offshore CO_2 geological storage (US$68.5 million, 2011-2015). The research program of Korea Ocean Research and Development Institute (KORDI) supported by MLTM is categorized into three parts, which are: 1) survey, screening and selection of offshore geological storage sites; 2) development of transport infrastructures and R&D on the safety; and 3) protection of marine environment.

To promote CCS deployment in Korea, the national CCS master action plan also includes establishing the national networks for technology development, demonstration, and law and regulatory framework: e.g., Korea CCS Association (KCCSA) for demonstration and deployment under MKE (November 2010), CCS R&D Center for technology innovation under MEST, and CCS Environmental Center for law and regulatory framework under ME and MLTM.

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 MWe 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 to 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

The Carbon Capture, Transport and Storage (CATO) R&D program can be regarded as the national research program on CCS in the Netherlands. The CATO program, now called CATO-1, was implemented by a strong consortium of 17 Dutch partners from industry, research institutions, universities, and environmental organizations, led by the Utrecht Centre for Energy Research (UCE). Total budget was €25.4 million, the Dutch government supported with €12.7 million through the BSIK subsidy program, managed by SenterNovem. CATO-1 ran from 2004 until the end of 2009.
http://www.co2-cato.nl/

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 that 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. Industry and government set the priorities within the research program: the "problem owners" are leading. Budget amounts up to €60 million, equally divided between industry and government. The core of the CATO-2 program (approximately 70 percent of the R&D effort) exists of 11 working 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 five to ten years) research.

CATO-2 research will be performed in five subprogram lines: CO_2 Capture; Transport and CCS Chain Integration; Subsurface Storage and Monitoring of CO_2; Regulation and Safety; and Public Perception. Dissemination and international cooperation are listed under program coordination.

Phase 1 (CATO-2A) of the program ran from 2009 to 2010 and has been completed. Focus was on organizing cooperation, evaluating R&D focuses, and establishing exchange with planned pilot and demo projects. Phase 2 (CATO-2B) will run from 2011 to 2014. Although some planned projects will not start for the time being as a result from changes in Dutch policy (no storage onshore), all industrial-orientated partners will keep to the program. http://www.co2-cato.nl/

The CAPTECH program was formulated as an add-on to the CATO-1 program. Focus of this research program was the development of high(er) efficient capture technologies, including plant integration. CAPTECH was a research program of six Dutch consortium partners. The program ran from 2006 through the end of 2010 and was coordinated by ECN. The aim of the consortium was the qualification of CO_2 capture technologies with power plant efficiency losses less than five percentage points, resulting in capture costs not higher than 20 to 30 €/ton of CO_2, depending on fuel type. The budget of the program was €2.5 million per year, and was financially supported by Dutch government through the EOS energy research strategy program. http://www.co2-captech.nl/

Norway

Norway has a significant public budget for RD&D related to CCS, and most of the budget is channeled to the RD&D program CLIMIT (http://www.climit.no/?language=UK). This program is run in collaboration between state-owned Gassnova SF and the Research Council of Norway, and the annual budget from the Norwegian Government is approx. US$17 million for R&D and US$15 million for pilot and demonstration projects. The program covers the full CCS chain with capture, transport, and storage of CO_2. The program has earlier only supported RD&D on CCS related to fossil-based power production, but the mandate for the program was extended in 2010 to also include CO_2 capture from industrial sources. The Climate program was established in 2005 and its impact has been a huge mobilization of universities, research institutes and companies to address CCS in their research activities. As a result Norway has played an important role when it comes to closing knowledge gaps related to CCS.

Norway has established two centers for environmental-friendly energy research with the objective to conduct concentrated, focused and long-term research of high international caliber in order to solve specific challenges related to CCS. The BIGCCS center (http://www.sintef.no/projectweb/bigccs/), established in 2009, addresses R&D gaps within the full CCS chain, including capture, transport and storage of CO_2. The center is granted US$ 3.6 million in public support annually for eight years. The SUCCESS center (http://www.fmesuccess.no/) was established in 2010 and focuses only on CO_2 storage, and is granted US$ 1.8 in public support annually for eight years. The two centers include several universities and research institutes and are supported by several industrial partners. Expected impacts from the two new centers include high level research that will close R&D gaps related to CCS.

Several pilots for CCS are in operation or under construction in Norway. The Technology Center Mongstad (TCM) is under construction and will test two different capture technologies when it is commissioned in late 2011 or early 2012. The capacity will be 100,000 tonnes of CO_2 captured annually. CO_2 capture by amine and chilled ammonia technologies will be tested. TCM will be the world's largest facility for testing and improving CO_2 capture, and significant R&D activities are planned at TCM the next years. (http://www.tcmda.no/)

The CO_2 Field Lab project is a pilot for CO_2 storage that is being established at Svelvik outside Oslo. The objective is to establish standards for monitoring by obtaining valuable knowledge about monitoring of CO_2 migration in geological formations. This will enable detection of possible CO_2 leakage at the earliest possible stage. (http://www.sintef.no/co2fieldlab)

Another CO_2 storage pilot, the Longyearbyen CO_2 Lab, has been established at Svalbard. An aquifer suitable for CO_2 storage has been identified, and injectivity was verified during extensive testing in 2010. Injection of CO_2 at pilot scale is expected to start in 2012. (http://co2-ccs.unis.no/)

A pilot for CO_2 capture has been built at Tiller outside Trondheim, allowing extensive testing of amines and other solvents for CO_2 capture. The pilot has paved way for a big R&D program, SOLVIT, where SINTEF together with Aker Clean Carbon is working on developing new and improved solvents that can accelerate commercialization of CO_2 capture technology.

A CO_2 capture pilot related to a cement plant is planned in Norway. Norcem has started a feasibility study for a capture pilot at its cement plant close to Porsgrunn at the south-east coast of Norway.

With many planned and ongoing R&D activities on CCS all over Europe it is without doubt a need for coordination of the efforts. This is addressed in the ECCSEL project, short for European Carbon dioxide Capture and Storage Laboratory Infrastructure. This project was proposed by NTNU and SINTEF on behalf of the Norwegian Government, and put on the official European Strategy Forum on Research Infrastructures (ESFRI) updated Roadmap in 2008. ECCSEL is planned to be in operation by 2015 as a strong and coordinated pan-European distributed Research Infrastructure within CCS. The ECCSEL preparatory phase started January 2011 with NTNU as project leader.

Poland

The Energy Policy of Poland includes CCS as part of the government's energy strategy. A draft of a legal act (e.g. the new "Geological and Mining Law") which transposes the EU CCS Directive into national Polish Law has been prepared and assumptions approved by the Cabinet. Full legislation related to geological sequestration of CO_2 is expected to be implemented by October 2011.

A program launched by the Polish Ministry of Environment seeks to identify suitable storage sites, with a budget of €8 million. A research project concerning a pilot CO_2 injection into saline aquifers in central Poland initiated by the Ministry of Environment and supported by domestic power companies is to be launched soon. The Polish Government has also formally endorsed the two CCS demonstration projects being developed at Bełchatow (EEPR grant awarded, project submitted also to the EU NER 300 program) and Kędzierzyn (project temporarily suspended).

The Polish Government's approach to financing CCS demonstration projects 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 centers, 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.

The Atlas on Geological Storage of Carbon Dioxide in South Africa was launched in September 2010. 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 Kingdom

CCS-related activities in the UK include research, applied R&D, pilot-scale development and demonstration, as well as the development of the legal and regulatory frameworks necessary to support the commercial deployment of CCS. These activities are supported by a number of agencies, partnerships and government departments as follows.

The Research Councils UK Energy Programme, http://www.rcukenergy.org.uk/, funds the innovative CCS research to help make this technology viable; trains a generation of skilled people to deploy it and helps shape the policies that will accelerate it from small-scale demonstration to full-scale deployment. Support has grown in scale over recent years to now cover a large portfolio of projects covering many major grants, consortia and capacity building activities in universities and research institutes, usually in partnership with industry. Examples of recent consortia funded are on the potential ecosystems impacts of geological carbon storage and multi-scale whole CCS systems modeling. Other recent support established consortia focused on capture technologies and transport pipelines. Investments have been made to develop links with China in research in CCS technologies and cleaner fossil fuels. Future activities will look at strengthening links with the United States. An Engineering Doctorate Centre in Efficient Fossil Energy Technologies is working with many industrial partners to develop engineering research leaders to tackle the CCS challenges. Many of the projects also look at public engagement aspects of CCS.

The Technology Strategy Board (TSB), http://www.innovateuk.org/, is an executive non-departmental public body sponsored by the UK government's Department for Business Innovation and Skills. The TSB stimulates technology-enabled innovation in the areas that offer the greatest scope for boosting UK growth and productivity. Low-carbon energy generation and supply, and particularly CCS, is a priority area identified by the TSB for investment and support for applied R&D and pilot plant demonstration. In 2009, the TSB and the UK government's Department for Energy and Climate Change jointly funded a number of collaborative R&D projects in CCS with grants totaling around £15 million. The funded projects focused on a range of technologies including advanced CO_2 capture, development of CO_2 monitoring devices and technologies to improve plant efficiency, essential in minimizing the penalties of CO_2 capture. The largest individual project funded is the advanced amine, post-combustion capture pilot plant project valued at around £20 million, with £6 million coming from public sector. This pilot plant will be one of the largest pilots in Europe when commissioned in early 2011. The TSB has also funded a number of smaller feasibility studies looking at earlier stage R&D in areas such as alternative uses of CO_2, algae capture, and CO_2 storage and transport.

The Energy Technologies Institute (ETI), http://www.energytechnologies.co.uk, is a limited liability partnership between the UK government and international industrial companies with a strong focus on energy. The ETI has an integrated CCS program aimed at developing technologies for UK application to help it meet its 2020 to 2050 CO_2 reduction targets. Activities include: a major CO_2 storage appraisal project (to be completed in 2011) aimed at providing a realistic, defensible and fully auditable assessment of potential CO_2 storage capacity in the UK; a study of UK requirements for storage MMV has been completed and a technology development project is expected to be launched in 2011; identification of key 'next generation' capture technologies with the potential for lower cost, performance impact and environmental footprint; technology development and demonstration projects are being developed which will start in 2011 or 2012 with the aim of accelerating technology development to enable commercial application in the 2020s (‘second wave’ technologies) and 2030s (‘third wave’); a project is currently being commissioned to develop a whole-chain CCS modeling tool-kit, aimed at improving understanding of operational issues for future CCS systems; a project has been launched to assess the viability of mineralization in a UK context (completes late 2011).

The UK Government’s Department for Energy and Climate Change (DECC), http://www.decc.gov.uk/, through its Office of Carbon Capture and Storage (OCCS), is tasked with facilitating the delivery of CCS in the UK and helping to promote its rapid deployment globally. As part of this, DECC is supporting two pilot-scale projects on oxyfuel combustion and post-combustion capture, and progressing with a program of four large-scale demonstration projects: the first, a >300MWe post-combustion capture demonstration on coal-fired power plant with CO_2 stored offshore, will operate from 2014, with the others brought into operation in a phased manner by 2018.

United States

The USDOE 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 United States program has appropriated US$692 million and US$404 million in Fiscal Year (FY) 2009 and FY2010, respectively, to support the development and demonstration of innovative technologies critical to coal systems with CCS including pre-, post-, and oxy-combustion capture processes; advanced gasification systems; hydrogen turbines; fuel cells; high strength materials and sensors; and CO_2 compression technologies.

The United States program also conducts R&D activities to support geologic storage of CO_2. These activities include development of novel storage technologies to improve containment and injectivity; monitoring, verification and accounting (MVA) tools to provide assurance of storage permanence; simulation and risk assessment to better predict and manage geologic storage projects; and CO_2 use and re-use. The program also promotes infrastructure development through the Regional Carbon Sequestration Partnerships and other small- and large-scale field tests to validate storage capacity and permanence. The National Risk Assessment Partnership is integrating observations and information from these efforts in the development of science-based predictive tools for quantifying long-term liability potentially associated with storage sites.

The program also includes large-scale demonstration projects to accelerate advanced carbon capture and storage technologies. This includes an additional US$3.4 billion from the American Recovery and Reinvestment Act of 2009 for CCS activities, including the demonstration of CCS technologies at commercial scale.

The USDOE National Energy Technology Lab (NETL) is involved in or tracking 106 CO_2 capture and/or storage or beneficial use projects being conducted throughout the United States at a private/public cost in excess of US$53 billion. The scope of the projects range from field testing and validation through commercial demonstration and deployment, and employ a vast array of CCS technologies in the power, commercial and industrial sectors. http://www.netl.doe.gov/technologies/carbon_seq/database/index.html

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 commercialization 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 commercialization, 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, Korea, Japan, the UK, 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). Four large-scale CCS projects are already in operation, including: In Salah in Algeria, Sleipner and Snøhvit in Norway, and Weyburn-Midale in Canada. For one commercial-scale project (Gorgon in Australia), contracts are under development.

CCS RD&D activities must be conducted in parallel to ensure broad CCS deployment within the desired timeframe. 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 are outside the scope of this TRM.

Key changes and progress from earlier versions of the TRM

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 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 characterization 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 projects, 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, has 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 characterization, 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 shale still requires research and better understanding. Lately, with the advent of oil and gas production from shale 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).

The 2011 TRM places a storage emphasis on:

- Stronger emphasis on CCS integration and demonstration of complete CCS value chains including CO_2 source and capture, transport, and storage of CO_2;
- 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 programs 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 MWe 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 with 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 Organization 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 Section 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 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 optimized 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 ongoing, 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 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 MWe 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 MWe 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 sulfur 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., CLC, 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 tons per 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 pipelines 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, SOx, 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

PRIORITY ACTIVITIES

- 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 harbor)
- 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 worldwide 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 obtaining 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 behavior 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 develop 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

PRIORITY ACTIVITIES

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 behavior

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 methods for improving resolution
- Compile baseline surveys of 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 where relevant
- 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 production. 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. Unmineable 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 unmineable coal seams relate to coal properties including the permeability of certain coal types and the behavior 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 a 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 coal bed 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 shale 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, shale, 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 shale 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 optimized 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 analyzed 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, United States as part of the USDOE-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 **Characterization of storage sites** • Location and characterization 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 behavior 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 mineralization, 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

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MODULE 4: TRM

4.1. The Role of the CSLF

The CSLF, consistent with its Charter, has catalyzed 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 organizations 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 the tables starting on page 108 below.

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	• Establish methodologies for estimating site-specific and worldwide storage capacity • Develop national and global atlases of CO_2 storage site and capacity • Determine allowable impurities in the CO_2 injected for storage • 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; and
- Increasing public communication to increase the public knowledge of CCS; and

- Working to overcome hurdles regarding regulatory and financial issues.

A summary of the current key milestones and TRM for the CSLF. Improved cost-effective technologies and long-term safe storage of CO_2 at 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 injection and MMV • Establish methodologies for 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

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.	
DEMONSTRATION AND INTEGRATION	• Establish operational experience and lessons learned with CCS • Demonstration of 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

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.	
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

€	Euros
£	United Kingdom Pounds Sterling
A$	Australian Dollars
ADEME	French Environment and Energy Management Agency
ADM	Archer Daniels Midland Company
AEP	American Electric Power
ANLEC R&D	Australian National Low Emissions Coal Research and Development Ltd
ANR	French National Research Agency (l'Agence Nationale de la Recherche)
BSIK	Besluit Subsidies Investeringen Kennisinfrastructuur (Dutch infrastructure investment program)
C$	Canadian Dollars
CACHET	European Union research program
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 Union program)
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 (China)
CERP	Carbon efficient recovery and processing
CERTH/ISFTA	Centre for Research and Technology Hellas/Institute for Solid Fuels Technology and Application (Greece)
CESAR	CO_2 Enhanced Separation and Recovery Project
CETC	CANMET Energy Technology Centre (Canada)
CFBC	Circulating fluidized-bed combustion
CFE	Federal Electricity Commission (Mexico)
CH_4	Methane
CHP	Combined heat and power
CLC	Chemical looping combustion
CLR	Chemical looping reforming
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies (Australia)
COE	Cost of energy
COORETEC	German initiative on CO_2 reduction technologies for fossil-fired power plants
CPRS	Carbon Pollution Reduction Scheme
CSLF	Carbon Sequestration Leadership Forum
DECC	Department for Energy and Climate Change (United Kingdom)
DNV	Det Norske Veritas
ECBM	Enhanced coal bed methane
EC	European Commission
ECBM	Enhanced Coal Bed Methane

ECCSEL	European CO_2 Capture and Storage Laboratory
ECN	Energy Research Centre of the Netherlands
EEPR	European Energy Programme for Recovery
EERA	European Energy Research Alliance
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
ESFRI	European Strategy Forum on Research Infrastructures
ETI	Energy Technologies Institute (United Kingdom)
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
FY	Fiscal Year
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 sulfide
HECA	Hydrogen Energy California Project
HMR	Hydrogen membrane reforming
HSE	Health Safety and Environmental
IEA	International Energy Agency
IEA GHG	IEA Greenhouse Gas R&D Programme
IGCC	Integrated Gasification Combined-Cycle
IIE	Institute of Electrical Research (Mexico)
INRS	Institut National de la Recherche Scientifique (France)
IP	Intellectual property
IPAC-CO_2	International Performance Assessment Centre for Geologic Storage of CO_2 (Canada)
IPCC	Intergovernmental Panel on Climate Change
ITC	International Test Center for CO_2 Capture (Canada)
ITM	Ion transfer membrane
KEPRI	Korea Electric Power Research Institute
kg	Kilograms
km	Kilometers
KAPSARC	King Abdullah Petroleum Studies and Research Centre (Saudi Arabia)

KAUST	King Abdullah Petroleum University of Science and Technology (Saudi Arabia)
KCCSA	Korea Carbon Capture and Storage Association
KORDI	Korea Ocean Research and Development Institute
LCA	Life Cycle Assessments
LCOE	Levelized Cost of Electricity
LHV	Lower heating value
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas (consists primarily of propane and butane)
KWh	Kilowatt-hour
m^3	Cubic meters
ME	Ministry of Economy (Korea)
MEST	Ministry of Education, Science and Technology (Korea)
METI	Ministry of Economy, Trade and Industry (Japan)
mg/L	Milligrams per liter
MGSC	Midwest Geological Sequestration Consortium (United States)
MILD	Moderate or intense low-oxygen dilution (a form of combustion)
MKE	Ministry of Knowledge Economy (Korea)
MPa	Megapascals, SI unit of pressure (10^6 pascals)
Mt	Megatonnes (millions of metric tons)
Mt/a	Megatonnes per annum -or- megatonnes per year
$MtCO_2$	Megatons of carbon dioxide
MILD	Moderate and/or Intensive Low Oxygen Combustion
MLTM	Ministry of Lands, Transportation and Maritime Affairs (Korea)
MMV	Measurement, Monitoring and Verification
MOSF	Ministry of Strategy and Finance (Korea)
MW	Megawatts, SI unit of power
MWe	Megawatts, SI unit of power, “e” denotes electricity output
MWh	Megawatt-hour
MWth	Megawatts, SI unit of power, “th” denotes thermal capacity
N_2	Nitrogen
NETL	National Energy Technology Laboratory (United States)
NGCC	Natural Gas Combined Cycle (also referred to as CCGT – Combined Cycle Gas Turbine)
NH_3	Ammonia
Nm^3	“Normal” cubic meters (i.e., cubic meters measured at standard temperature and pressure)
NOAK	Nth-of-a-kind
NRAP	National Risk Assessment Partnership (United States)
NSW	New South Wales, Australia
NTNU	Norwegian University of Science and Technology
NZEC	Near-Zero Emissions Coal project
O_2	Oxygen
OECD	Organization for Economic Co-operation and Development
OGS	National Institute of Oceanography and Experimental Geophysics (Italy)
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
PC	Pulverized Coal (sometimes referred to as PF – Pulverized Fuel)

PCC	Pulverized Coal Combustion
PCOR	Plains CO_2 Reduction Partnership (United States and Canada)
PSA	Pressure swing adsorption
PTRC	Petroleum Technology Research Centre (Canada)
R&D	Research and Development
RCSP	Regional Carbon Sequestration Partnerships (United States and Canada)
RD&D	Research, development, and demonstration
RCI	Rotterdam Climate Initiative (Netherlands)
RISCS	Research in impacts and safety in CO_2 Storage
RITE	Research Institute of Innovative Technology for the Earth (Japan)
ROAD	Rotterdam Afvang en Opslag Demonstratie project
SER	Sorption in Enhanced Reforming
SEWGS	Sorption Enhanced Water Gas Shift
SRA	Strategic Research Agenda
t/a	Tonnes per annum -or- tonnes per year
TCM	Technology Center Mongstad (Norway)
Tonne	Metric ton (equal to 1,000 kilograms)
tpd	Tonnes per day
TRM	Technology Roadmap
TSA	Temperature swing adsorption
TSB	Technology Strategy Board (United Kingdom)
UCE	Utrecht Centre for Energy Research (Netherlands)
UK	United Kingdom
US$	United States Dollars
USA	United States of America
USDOE	United States Department of Energy
ULCOS	Ultra-low carbon dioxide steelmaking
ULYSSES	Undersea Large-scale Saline Sequestration and Enhanced Storage
WESTCARB	West Coast Regional Carbon Sequestration Partnership (United States and Canada)
WGS	Water gas shift
ZEP	Zero Emission Platform
ZEPP	Zero Emission Power Plant, Zero Emission Fossil Fuel Power Plants