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TECHNICAL GROUP
SUPPLEMENTAL DOCUMENT

CSLF Technology Roadmap
draft of 23 March 2009

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Carbon Sequestration Leadership Forum

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SUPPLEMENTAL MEETING DOCUMENT

CSLF TECHNOLOGY ROADMAP
(DRAFT OF 23 MARCH 2009)

Note by the Secretariat

The CSLF Technology Roadmap was originally created in 2004 and was approved by the CSLF at the Melbourne ministerial meeting in September 2004. The CSLF Technical Group agreed at its Paris meeting in 2007 to create a working group under the Projects Interaction and Review Team (PIRT) for updating the Roadmap, and progress reports concerning Roadmap updating activities were made at the three Technical Group meetings that were held in 2008.

A two-day meeting of the PIRT working group in Canberra, Australia, in September 2008 resulted in many suggested revisions to the Roadmap. During the first part of 2009, follow-on work by a team from Australia's Global Carbon Capture and Storage Institute resulted in a complete preliminary draft. Comments from PIRT members on this draft were considered during a working group teleconference on 12 March 2009 and this draft takes into account all comments received as of 17 March 2009.

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CSLF Technology Roadmap

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MODULE 0: INTRODUCTION

0.1 Context

The first CSLF Technology Roadmap was developed in 2004 to identify promising directions for research in carbon dioxide capture and storage (CCS). Since this time there has been rapid growth in interest and the application of carbon dioxide (CO_2) capture and storage technology around the world.

This updated Technology Roadmap takes account of the significant accomplishments that have occurred in the period from 2004 to early 2009 and identifies key knowledge gaps and hence areas where further research should be undertaken.

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

0.2 The Purpose of the CSLF Technology Roadmap

This Technology Roadmap is intended to provide a pathway toward the commercial deployment of integrated carbon dioxide capture, transport and storage technologies. Specifically, the Technology Roadmap focuses on:

- Achieving commercial viability and integration of CO_2 capture, transport and storage;
- Developing an understanding of global storage potential, including matching CO_2 sources with potential storage sites and infrastructure 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 demonstrations.

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

0.3 Structure of this Technology Roadmap

This Technology Roadmap comprises four modules. The first module briefly describes the current status of carbon dioxide capture 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 describes various approaches toward integrated CO_2 capture, transport and storage and indicates achievable milestones.

MODULE 1: CURRENT STATUS OF CO_2 CAPTURE AND STORAGE TECHNOLOGY

1.1. CO_2 Capture

CO_2 is emitted to 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;
- from agricultural sources; and
- from automobiles and other mobile sources.

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

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

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 essentially pure CO_2 is available for storage. Cost depends on many variables including the type and size of plant and the type of fuel used. Currently, the addition of CO_2 capture can add 50-100% (or more) to the investment cost of a new power station (OECD/IEA, 2008).

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

1.1.1. 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. 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 1 is a simplified diagram of a coal-fired power station with post-combustion capture of CO_2.

Post-combustion capture is applicable to coal-fired power stations but additional measures, such as desulphurisation, are needed to 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.

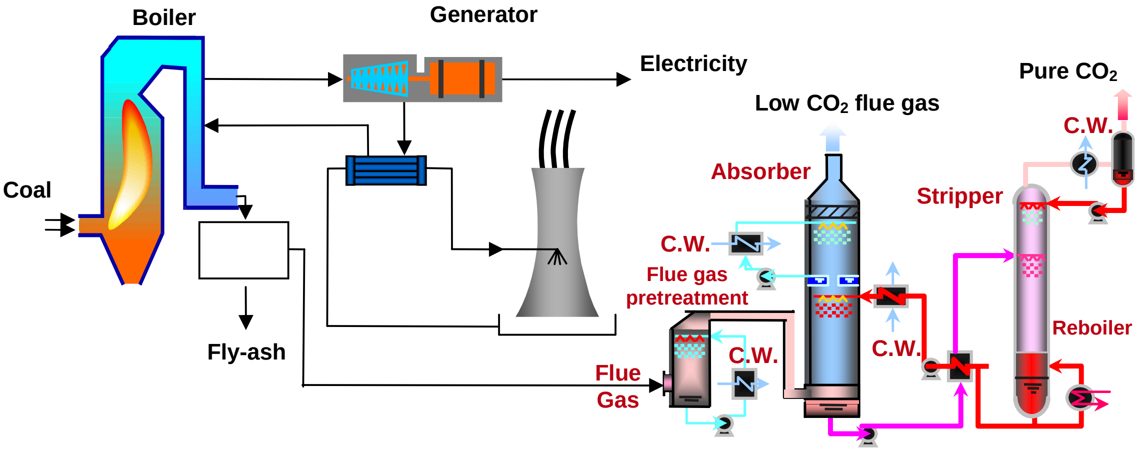


Figure 1. Coal-fired power station with post-combustion capture of CO_2 (courtesy of the Commonwealth Scientific and Industrial Research Organisation).

1.1.2. Pre-combustion Capture

Pre-combustion capture increases the CO_2 concentration, 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. 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 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 captured CO_2.

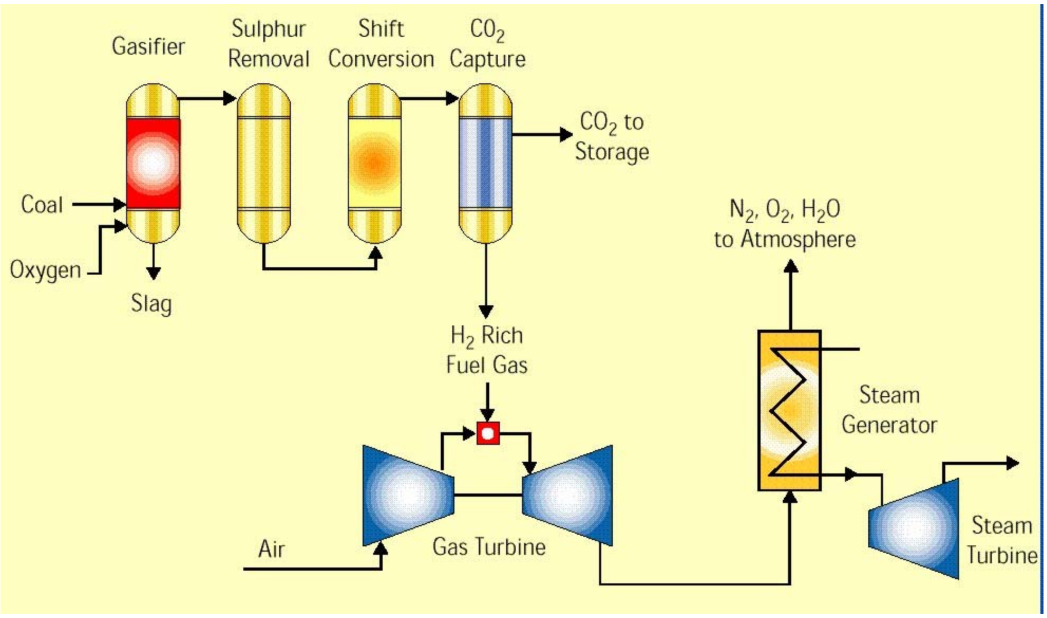


Figure 2. Coal-fired Integrated Gasification Combined Cycle (IGCC) process with pre-combustion capture of CO_2 (courtesy of the IEA Greenhouse Gas R&D Programme)

1.1.3. 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 MW_{th}).

1.1.4. Type of Capture Technology

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

1.1.4.1. 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 over 60 years in the refining and chemical industries for removal of hydrogen sulphide (H_2S) and CO_2 from reducing gases. Only a few facilities use amines to capture CO_2 from oxidising gases such as flue gas.

1.1.4.2. 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 integrated gasification combined cycle (IGCC) process, located upstream of the gas turbine, would have a CO_2 concentration of about 35-40% and a total pressure of 20 bar or more. Under these pre-combustion conditions, physical solvents such as those in the Rectisol, Selexol, and Fluor processes may be preferable because they have a larger CO_2 capacity and CO_2-solvent separation can be accomplished by reducing the stripper pressure, resulting in lower regeneration energy consumption.

1.1.4.3. 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 whilst 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 adsorption generally is not considered attractive for large-scale separation of CO_2 from flue gas because of low capacity and low CO_2 selectivity.

1.1.4.4. 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.

1.1.4.5. 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%), 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.

1.1.4.6. Other Capture Processes

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

1.1.5. The Effect of Fuel Type

The presence of fuel contaminants and specific combustion products impose additional constraints on the choice and operation of CO_2 control technology. With coal-fired systems, particulates can erode turbine blades in IGCC plants, contaminate solvents and foul heat exchangers in absorption processes, and foul membranes or sorbents in the new capture processes. Sulphur and nitrogen compounds must also be reduced to low levels before CO_2 capture since 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.

1.1.6. 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, for CO_2 capture retrofit may be limited by physical site conditions and proximity to CO_2 transport 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% more than incorporating CO_2 capture into a new power station (McKinsey, 2008).

1.1.7. Other Sources of CO_2

Globally, stationary energy/electricity generation from fossil fuels is responsible for just over one-third of all emissions of CO_2. The emissions from other, large industrial sources, including iron and steelmaking, natural gas processing, petroleum refining and petrochemical processing and cement production amount to about 25% 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 for capturing CO_2 in these processes as well. The high CO_2 concentrations of some of these streams, such as 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 EAF routes) as one of a number of pathways for a low carbon future. The European Ultra Low Carbon Dioxide Steelmaking program (ULCOS http://www.ulcos.org/en/about_ulcos/home.php) is one such initiative that includes CCS as an element of technological developments.

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

1.1.8. Hydrogen Production

Commercial production of hydrogen (H_2) currently involves synthesis from fossil fuels in a multi-step process similar to that described in 1.1.2. Addition of CO_2 capture technology to this process would require relatively small changes and could allow the transition to energy systems which make greater use of H_2 as an energy carrier. Further improvements of the process are possible.

1.1.9. 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.

1.2. CO_2 Transmission

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

1.2.1. 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 purposes. About 30 million tonnes of CO_2 per year is currently transmitted through over 3000km 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 enhanced oil recovery 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 3 indicates the likely range of costs for the transmission of CO_2 through onshore and offshore pipelines.

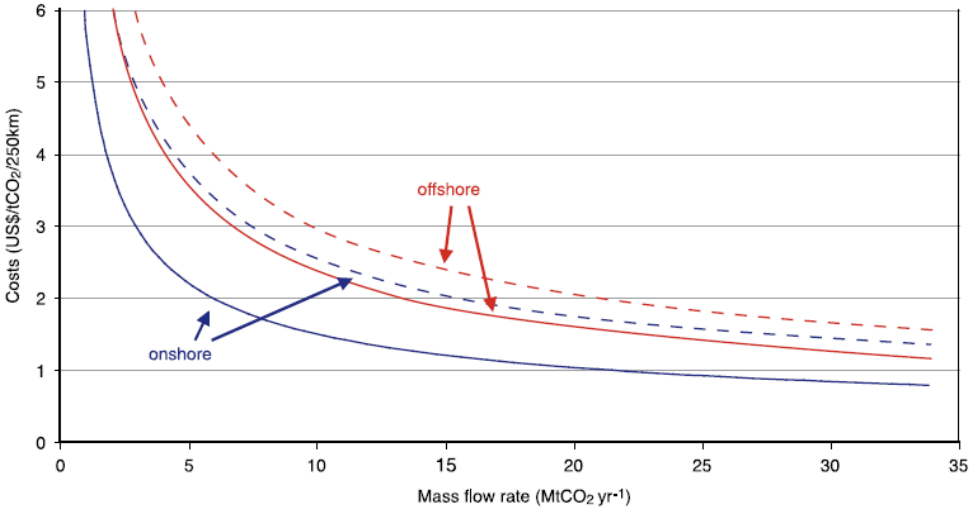


Figure 3. Range of CO_2 transport costs for onshore and offshore pipelines per 250 km. Solid lines show low range values and dotted lines high range values (Source: OECD/IEA, 2008).

1.2.2. Ship Tankers

Large scale tanker transport of CO_2 from capture sites located near appropriate port facilities may occur in the future. The CO_2 would be transported in marine vessels such as those currently deployed for LNG/LPG transport as a pressurised cryogenic liquid (at high pressure/low temperature conditions). This would require relatively high purity CO_2. Ships offer increased flexibility in routes and they may be cheaper than pipelines, particularly for longer distance transportation. It is estimated that the transport of 6MtCO_2 per year over a distance of 500km by ship would cost about 10US$/t$CO_2$, while transporting the same 6MtCO_2 a distance of 1250km would cost about 15US$/t$CO_2$ (OECD/IEA 2008).

1.3. Storage of CO_2

1.3.1. General Considerations

Captured CO_2 can be stored:

- in certain types of geological formations;
- through mineralisation and industrial use; and possibly
- by injecting it into the ocean.

Storage of CO_2 must be safe, permanent, 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).

1.3.2. 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 alongside hydrocarbons for millions of years.

Subject to specific geological properties, several types of geological formations can be used to store CO_2 (Figure 4). Of these, deep saline-water saturated formations, depleted oil and gas fields, and unmineable coals have the greatest potential capacity for CO_2 storage. CO_2 can be injected and stored as a supercritical fluid in deep saline formations and depleted oil and gas fields, where it migrates, like other fluids (water, oil, gas) through the microscopic, interconnected pore spaces in the rock. Supercritical conditions for CO_2 occur at 31.1°C and 7.38Mpa, which occurs approximately 800 m below surface level.. When supercritical CO2 has properties of both a gas and a liquid and is 500-600 times more dense than at surface conditions, while remaining more buoyant than formation brine. CO_2 can also be injected into unmineable coal beds where it is stored by adsorption onto the coal surface, sometimes enhancing coal bed methane production.

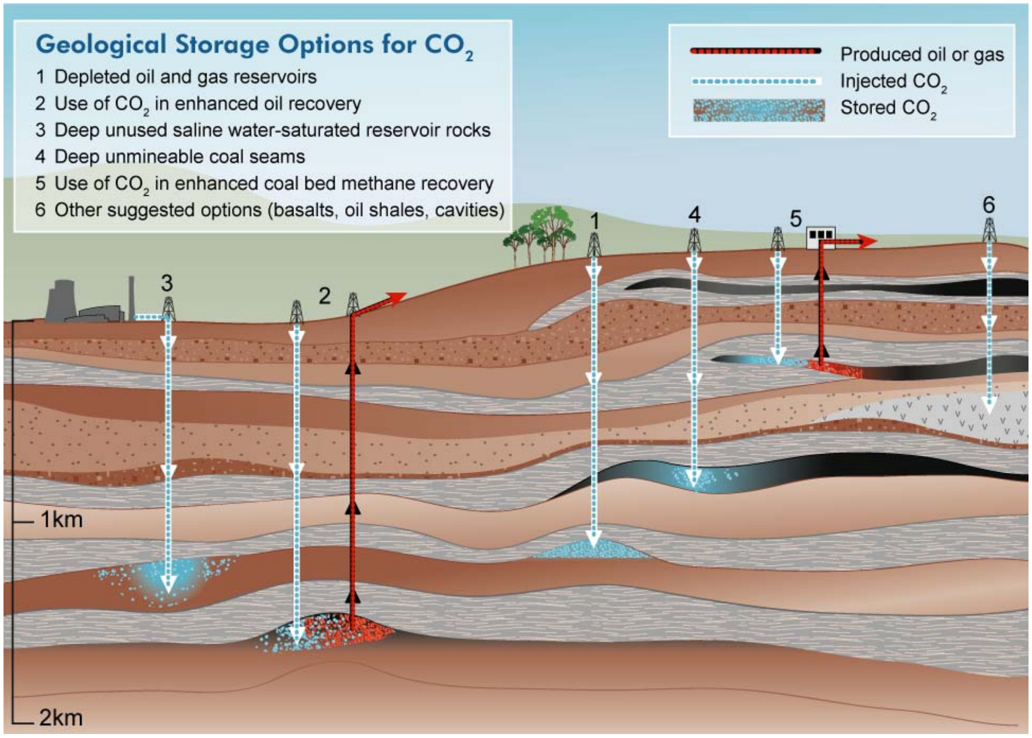


Figure 4. Geological options for CO_2 storage (courtesy of the Cooperative Research Centre for Greenhouse Gas Technologies).

<u>1.3.2.1. Deep Saline Formations</u>

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 permeability to allow large volumes of CO_2 to be injected in a supercritical state and a low permeability cap rock, or seal, to prevent CO_2 leakage 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, huge available volumes, and lack of any commercial competing use (which largely explains why relatively little is known about their storage potential).

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 for climate change mitigation. Injection of approximately one million tonnes of CO_2 per year (captured from a natural gas stream) into the Utsira Formation at a depth of about 1000m below the sea floor, began in 1996. The CO_2 is being monitored through an international project established by StatoilHydro with the IEA Greenhouse Gas R&D Programme (StatoilHydro, 2008). Following Sleipner, several other large-scale deep saline formation storage projects have also come on line, including:

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

Both projects have associated monitoring programs.

1.3.2.2. 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 closure (e.g. a 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 reservoirs 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, also 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 all oil fields contain unproduced oil after production has ceased, whereas nearly all of the gas in gas fields can be produced. Enhanced oil recovery (EOR) methods, using water, gas 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 enhanced oil recovery, while CO_2 injection into depleted gas reservoirs may not result in new 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. Depleted gas fields possess significant storage capacity due to their large size and high recovery factor (>80%), as opposed to oil reservoirs whose recovery factor is in the 25% range. Also, deep saline formations around, beneath or above depleted fields could be used for CO_2 storage.

1.3.2.3. Unmineable Coal Beds

Coal beds below economic mining depth can also be used to store CO_2. Carbon dioxide injected into unmineable coal beds is adsorbed onto the coal and stored as long as the coal is not mined or otherwise disturbed. Methane, which occurs naturally with coal, will be displaced when CO_2 is injected and can result in enhanced coal bed methane (ECBM) production (discussed further in section 1.4.2).

Carbon dioxide storage in coal is limited to a relatively narrow depth range, between 600m and 1000m, and less than 1200m. Shallow beds less than 600m deep have economic viability and beds at depths greater than 1000m 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 formation; however, fracturing the coals and likely the unit above may increase the potential for CO_2 leakage. 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 4000 to 10,000 mg/l, depending on jurisdiction. In such cases the depth interval of coals potentially suitable for CO_2 storage will be further reduced.

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

1.3.2.4 Other Geological Storage Options

Other geologic 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 or saline formations. These 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.

1.3.3. Mineralisation

Nature's way of geologically storing CO_2 is the very slow reaction between CO_2 and naturally occurring minerals, such as magnesium silicate, to form the corresponding mineral carbonate.

Dissolution of CO_2 in water forms carbonic acid **-** *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. At present, this option would be considerably more expensive than others.

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

1.3.4. 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, solid, or 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.

In the study of ocean injection, environmental effects near the point of CO_2 injection are of primary concern. Recent concern about natural ocean acidification arising from absorption of CO_2 from the atmosphere makes this storage option much less acceptable. As stated in the IPCC's Fourth Assessment Report, "the uptake of anthropogenic carbon since 1750 has led to the ocean becoming more acidic, with an average decrease in pH of 0.1 units" (IPCC, 2007). As global atmospheric CO_2 levels increase, ocean acidification increases. Average global surface ocean pH is predicted to decrease by a further 0.14 to 0.35 units over the 21st Century (IPCC, 2007). Therefore deep ocean storage is not considered further in this report.

1.4. Uses for CO_2

Commercially produced CO_2 is an expensive product for enhancing oil, gas and coal bed methane production, biofixation, and for making industrial and food products. Cost offsets can be achieved by redirecting pure-stream CO_2 from capture projects. 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.

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

Conventional oil production techniques may only recover a small fraction. typically 5–15%, of oil in reservoirs (Tzimas et al., 2005). Secondary recovery techniques such as water flooding can increase recovery to 30–50% (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 enhanced oil recovery 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.

At the end of 2007, there were 95 active CO_2-EOR projects worldwide, the vast majority in the USA (Moritis, 2008). In 2005, 5.7 million tonnes of CO_2 was captured from six point sources for EOR use. The largest of these, the Dakota Gasification Plant in North Dakota, USA, provides 1.75 million tonnes of CO_2 annually to the Weyburn EOR project in Saskatchewan, Canada, some 330 kilometres away. This was the first major project designed to demonstrate the long-term effectiveness of CO_2 capture coupled with enhanced oil recovery. Currently about 3.2 million tonnes of CO_2 are injected for EOR at the EnCana and Apache fields at Weyburn each year, with approximately 35 million tonnes of CO_2 expected to be stored in total (Petroleum Technology Research Centre, 2008).

Enhanced gas recovery is different because it is possible to produce almost all of the original gas in place through primary production techniques. However, injection of CO_2 into a producing gas reservoir will help maintain reservoir pressure and increase the rate of gas production. Because of rapid CO_2 expansion in the reservoir, breakthrough will occur rather rapidly and CO_2 will be produced along with the gas, necessitating separation of the CO_2 from the natural gas, in a way mimicking the current operations at Sleipner and In Salah, and also 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 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.

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

1.4.2. Biofixation

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

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

1.4.3. Industrial Products

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

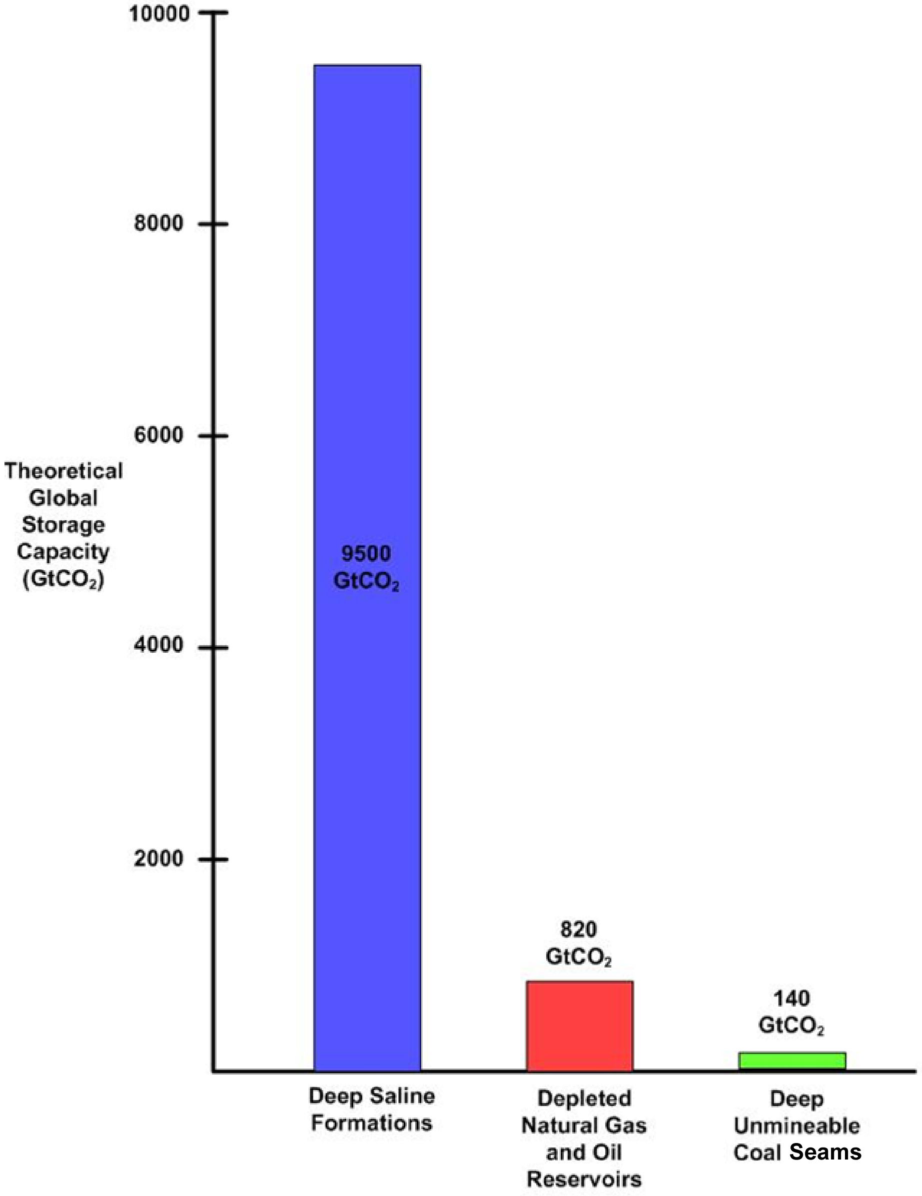
Since CO_2 is thermodynamically stable, significant energy is needed in its conversion for use as a chemical raw material. The additional energy requirement and cost may preclude its use as a chemical raw material in all but a few niche markets.

1.5. 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 cost on carbon. Storage of CO_2 in oil and gas reservoirs will have the advantage that the geology of reservoirs is well known and existing infrastructure may be adapted for CO_2 injection. The same does not apply to unmineable coal seams or storage in deep saline formations which collectively may be exposed to higher overall storage cost structures because of lack of offsets.

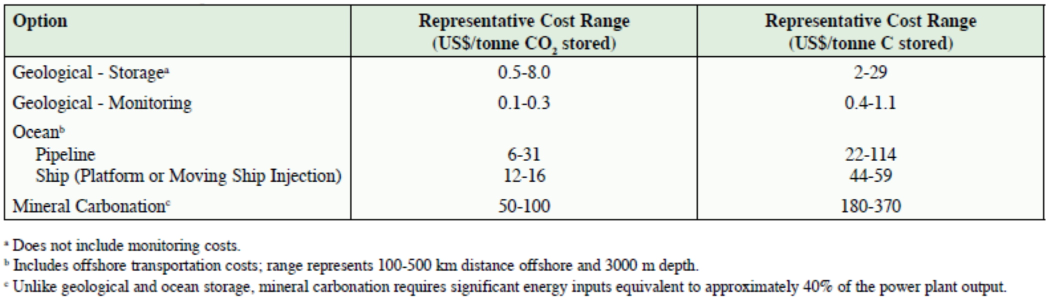
Figure 5 indicates the theoretical global storage capacity for deep saline formations, depleted oil and gas reservoirs and unmineable coal seams. Note that these capacity estimates are broad indications only, with high ranges of uncertainty, and include non-economical options.

Many factors influence the costs of storage and these are very site-specific (e.g. the number of injection wells required, onshore versus offshore, 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 6 (table) shows estimates of CO_2 storage costs.



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

Figure 5. 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 distance 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 6. Estimates of CO_2 storage costs (Source: IPCC, 2005)

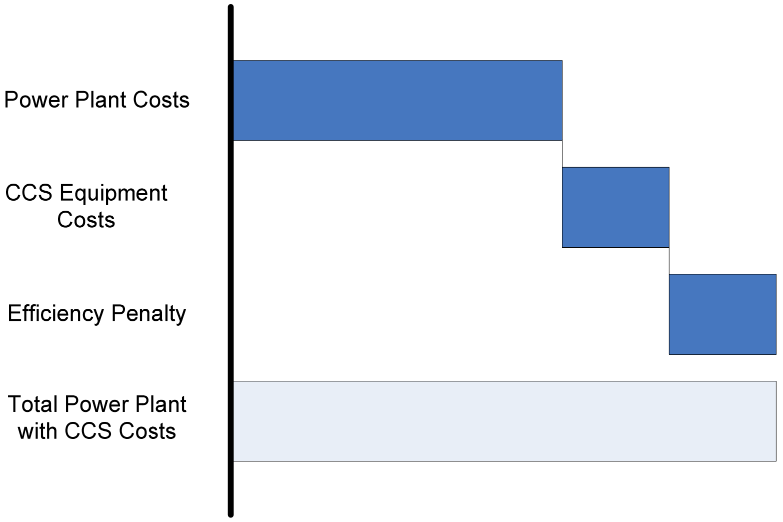
1.6 Power Station Performance and Costs: With and Without CO_2 Capture

The Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), McKinsey & Company and other organisations have evaluated the performance and costs of power generation options with and without CO_2 capture. These sources have been utilised in this Technology Roadmap but it should be noted that across the CCS industry a wide range of models, variables, units and values is used.

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

1.6.1. Power Station Performance

Figure 7 shows the conceptual costs associated with the capture of carbon dioxide 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 using the same fuel.



Source: McKinsey & Co., *Carbon Capture and Storage: Assessing the Economics*, 2008

Figure 7. 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 8.

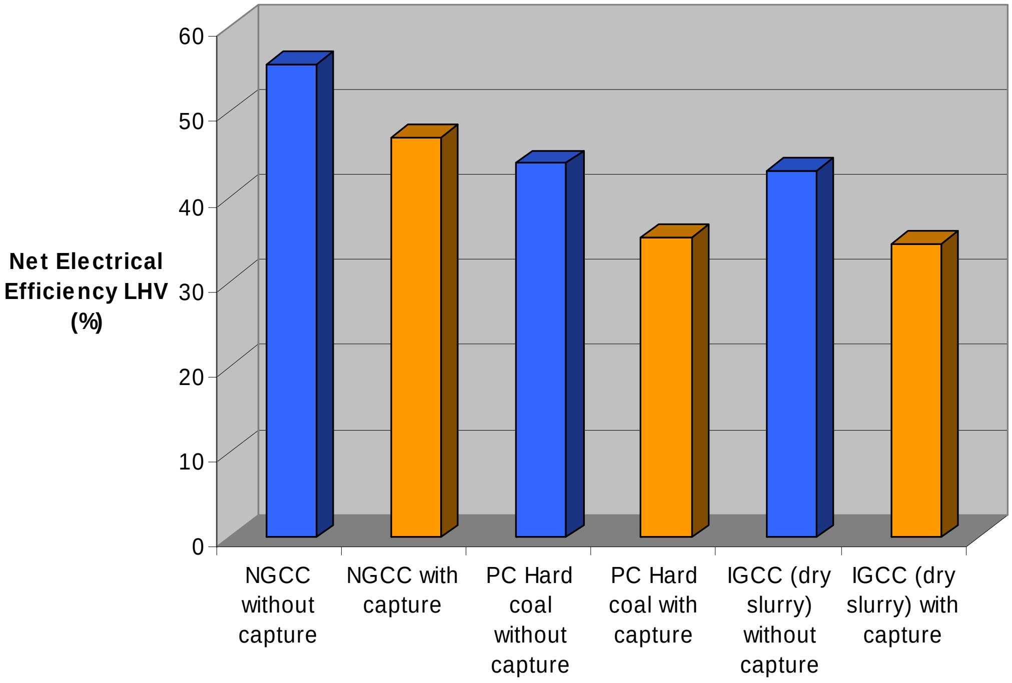
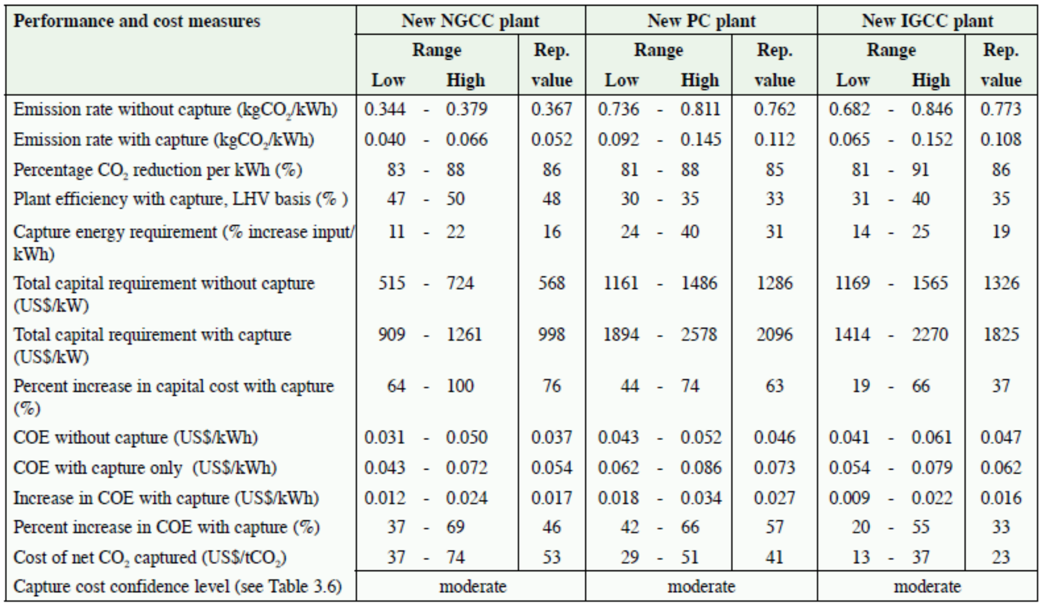


Figure 8. Power station Generation Efficiencies with and without the capture of CO_2 (Source: IEA Greenhouse Gas R&D Programme, 2007).

1.6.2. Power Generation Costs

On average, CO_2 capture and compression increases the capital cost of NGCC plant by 76%, a PC plant by 63%, and an IGCC plant by 37% (Figure 9). The order of capital costs is the same with or without CO_2 capture – the NGCC plant is least expensive and the IGCC plant is most expensive.



Performance and cost measures	New NGCC plant			New PC plant			New IGCC plant		
	Range		Rep. value	Range		Rep. value	Range		Rep. value
	Low	High		Low	High		Low	High	
Emission rate without capture (kgCO_2/kWh)	0.344	0.379	0.367	0.736	0.811	0.762	0.682	0.846	0.773
Emission rate with capture (kgCO_2/kWh)	0.040	0.066	0.052	0.092	0.145	0.112	0.065	0.152	0.108
Percentage CO_2 reduction per kWh (%)	83	88	86	81	88	85	81	91	86
Plant efficiency with capture, LHV basis (%)	47	50	48	30	35	33	31	40	35
Capture energy requirement (% increase input/kWh)	11	22	16	24	40	31	14	25	19
Total capital requirement without capture (US$/kW)	515	724	568	1161	1486	1286	1169	1565	1326
Total capital requirement with capture (US$/kW)	909	1261	998	1894	2578	2096	1414	2270	1825
Percent increase in capital cost with capture (%)	64	100	76	44	74	63	19	66	37
COE without capture (US$/kWh)	0.031	0.050	0.037	0.043	0.052	0.046	0.041	0.061	0.047
COE with capture only (US$/kWh)	0.043	0.072	0.054	0.062	0.086	0.073	0.054	0.079	0.062
Increase in COE with capture (US$/kWh)	0.012	0.024	0.017	0.018	0.034	0.027	0.009	0.022	0.016
Percent increase in COE with capture (%)	37	69	46	42	66	57	20	55	33
Cost of net CO_2 captured (US$/t$CO_2$)	37	74	53	29	51	41	13	37	23
Capture cost confidence level (see Table 3.6)	moderate			moderate			moderate		

Figure 9. A Summary of the CO_2 capture costs for new power stations based on current technology. Costs presented do not include the costs (or credits) for CO_2 transport and storage (Source: IPCC, Special Report on Carbon Dioxide Capture and Storage, 2005)

A NGCC plant without CO_2 capture has the lowest cost of electricity at 3.7¢/kWh. Adding CO_2 capture increases the cost by about 1.7¢/kWh. The addition of CO_2 capture to a coal plant increases the cost of electricity by 1.6 - 2.7¢/kWh depending on the cost of fuel and type of plant (see Figure 10). Further costs would be added to the supply of electricity when including the costs associated with the transport and storage of CO_2.

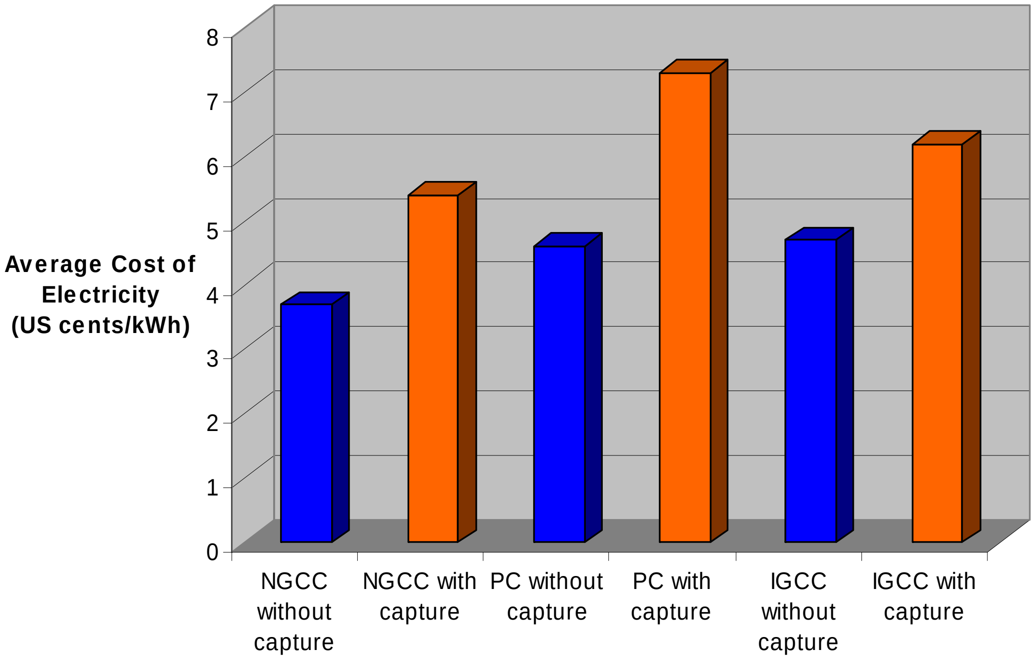


Figure 10. The average cost of electricity for power stations with and without CO_2 capture (Source: IPCC, Special Report on Carbon Dioxide Capture and Storage, 2005).

Figure 11 brings together information on power station capital costs, CCS costs and CCS efficiency penalty costs to provide estimates of the total cost of power station types with CCS. The graph is based on the data contained in Figure 9 and demonstrates what the total costs of CCS would be for a 500MW power station operating with 85% capacity factor.

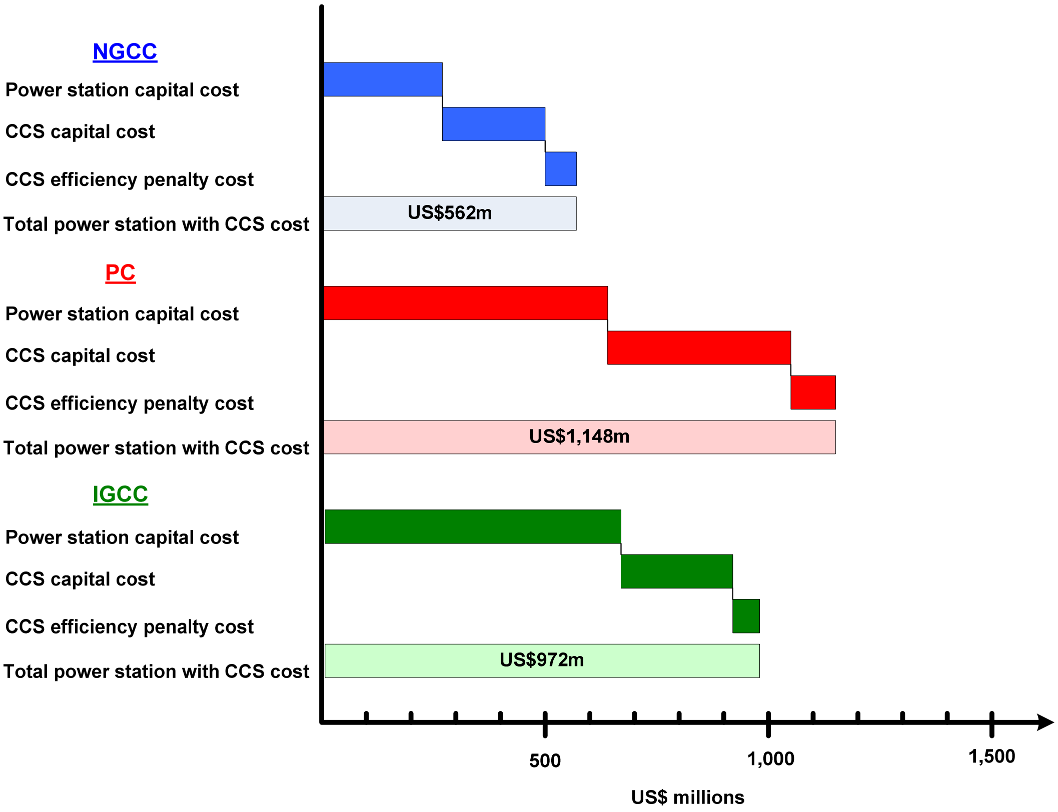


Figure 11. A comparison of the total cost of CCS for different power station types with a 500MW unit operating with 85% capacity factor (Source: IPCC, Special Report on Carbon Dioxide Capture and Storage, 2005).

1.7. Security of Storage

1.7.1. 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 techniques. The fact that CO_2 has been securely stored for millions of years, for instance in commercial gas fields, is important in gaining public acceptance of underground CO_2 storage (Miyazaki et al., 1990).

1.7.2. 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 transported around the world via pipelines and ships, and in many countries it is stored in geological formations to ensure constant supply. While small in comparison, significant quantities of CO_2 are routinely transported by pipeline in association with enhanced oil recovery projects (IPCC, 2005). Operating procedures and safety standards have been developed, and there is increasing experience with underground injection of CO_2.

There is little concern over the basic integrity of oil and gas fields used for CO_2 storage since the original contents remained trapped for millions of years. Care must be exercised to prevent reservoir over-pressurisation during injection as this could activate fractures and lead to leakage. The greatest concern about CO_2 storage in oil and gas fields is the integrity of the many wells drilled during the exploration and production phases of the operation. Cement degradation, casing corrosion, or damage to the formation near the well could result in leakage. But as in standard oilfield practise, there are mitigation strategies that can be put in place to ensure well integrity.

1.7.3. Understanding Geological CO_2 Leakage

Noting that sites of natural CO_2 leakage exist in many parts of the world, sites selected for underground storage for CO_2 will:

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

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

1.7.4. Risk Assessment

There are two types of risks involved in long term storage: environmental and safety. Extensive experience exists in the oil and gas industry for gas transport and injection, including $CO_{2.}$ As such, those risks are well understood. Modelling studies assist in assessing the long term behaviour and migration of stored CO_2. 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 contributing to the creation of a sound regulatory framework for geological storage of CO_2.

MODULE 2: ONGOING ACTIVITIES IN CO_2 CAPTURE AND STORAGE

2.1. Introduction

This module summarises ongoing activities on the capture and storage of CO_2. Figures 12 and 13 show the increase in global activities in CCS over the past four years based on currently available information from the IEA Greenhouse Gas R&D Programme and Cooperative Research Centre for Greenhouse Gas Technologies project databases. While there are other databases on CCS projects, there is broad differentiation in the project information provided and the terms and criteria used to define a project. Due to this information gap, Figures 12 and 13 may not be complete. This gap also highlights the need for collaboration on an internationally agreed CCS project database.

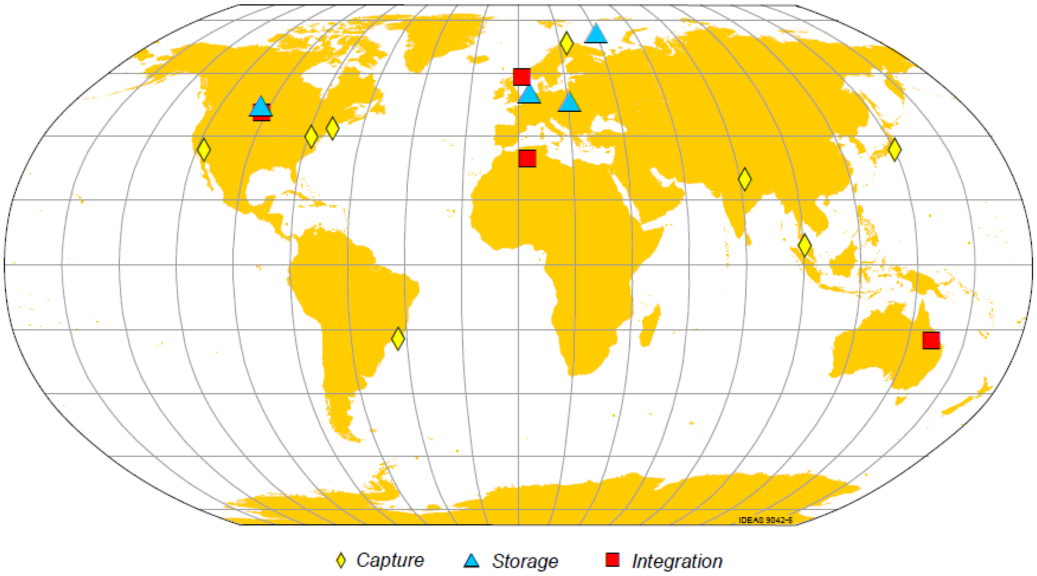


Figure 12. Commercial and demonstration CCS projects announced or commenced in or before 2004.

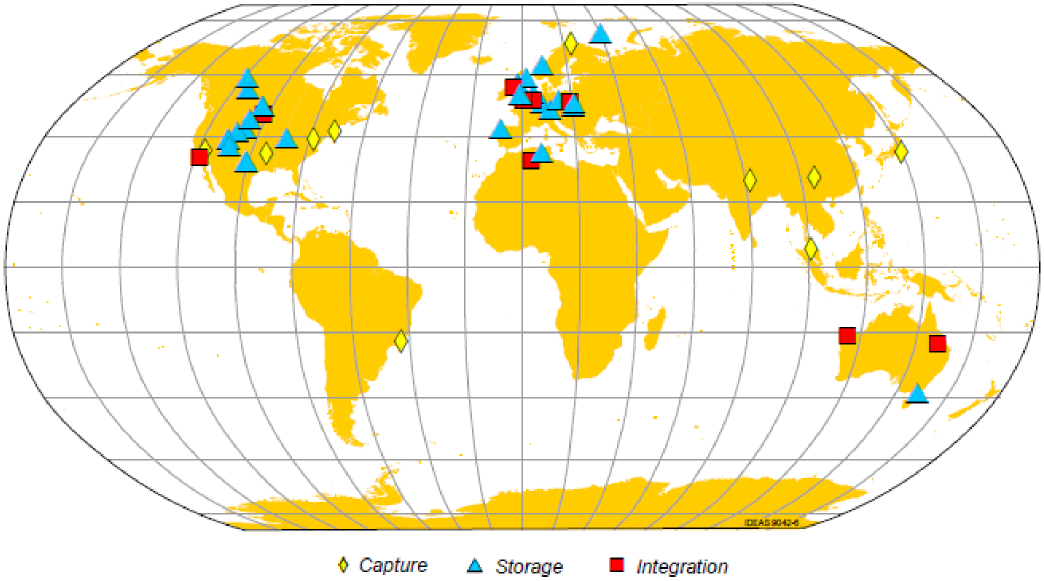


Figure 13. Commercial and demonstration CCS projects either announced or commenced before 2009.

2.2 CSLF Activities and Achievements

The CSLF 2004 Technology Roadmap identified six key activities to be carried out in the period 2004 to 2008 to address cost reductions, reservoirs and monitoring and verification (Figure 14).

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
Secure Reservoirs	• Initiate field experiments • Identify most promising reservoir types	• Develop reservoir selection criteria • Estimate worldwide reservoir "reserves"	• Large scale implementation
Monitoring and Verification Technologies	• Identify needs • Assess potential options	• Field tests	• Commercially available technologies

Figure 14. 2004 CSLF Technology Roadmap

Recently completed and ongoing activities of the CSLF include:

- The developed 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 web site www.cslforum.org.

2.3. Commercial Scale CCS Project Activities

This section presents a number of projects but not is not an exhaustive list that correlates with Figures 12 and 13.

Across the world there are four operational commercial-scale integrated CCS projects. These projects are motivated and/or linked to oil and gas production and include:

1. The **Sleipner project in Norway** (Statoil) where since 1996 more than 1 million tonnes per year (Mt/yr) of CO_2 has been captured during natural gas extraction and re-injected 1,000m below the sea floor into the Utsira saline formation. http://www.statoilhydro.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx
2. The **In Salah project in Algeria** (Statoil and BP) where since 2004 about 1 Mt/yr of CO_2 has been captured during natural gas extraction and injected into the Krechba geologic formation at a depth of 1,800m. http://www.statoilhydro.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx
3. **Snøhvit in Norway.** This liquefied natural gas (LNG) plant (Petoro, Statoil, TotalFinaElf, Gaz de France, Norsk Hydro, Amerada Hess, RWE-DEA, Svenska Petroleum) captures 0.7 Mt/yr of CO_2 and injects it into the Tubåsen sandstone formation 2,600m under the seabed for storage.

http://www.statoilhydro.com/en/technologyinnovation/protectingtheenvironment/carboncaptureandstorage/pages/captureandstorageofco2.aspx

4. The **Weyburn-Midale project in the USA** (EnCana – Apache) captures about 2.8 Mt/yr of CO_2 from a coal gasification plant, transports this by pipeline 320 km across the Canadian border and injects it into depleting oil fields where it is used for Enhanced Oil Recovery (EOR). http://www.netl.doe.gov/publications/factsheets/project/Proj282.pdf

Two pilot plant projects which are more focused on carbon dioxide capture and storage in the energy sector are:

1. The **Schwarze Pumpe pilot plant in Germany** (Vattenfall) which commenced operations in 2008. Based on an oxy-combustion concept, CO_2 is captured from the flue gas after deSOx and deNOx processes. It is planned to store CO_2 in a depleted gas field (Altmark) operated by Gaz de France. http://www.vattenfall.com/www/vf_com/vf_com/Gemeinsame_Inhalte/DOCUMENT/360168vatt/5965811xou/902656oper/1557089ccs/P02.pdf

2. The **Lacq pilot plant in France** (Total) which is planned to start in 2009. This is a 30 MW gas boiler which will use oxy-combustion capture technology; CO_2 will be transported in an 30 km existing pipe and will be stored in a very deep depleted gas field (4500m). http://www.total.com/static/en/medias/topic2627/lacq-pilot-information-dossier.pdf

In addition, there are also 20 other major project announcements from around the world. These include:

1. The **ZeroGen project in Australia**, which will use IGCC with pre-combustion capture technology at a 400MW coal-fired power station and store the CO_2 in deep saline formations in the Northern Denison Trough approximately 220 km from the plant. Demonstration is expected by 2012, with full-scale operation by 2017. http://www.zerogen.com.au/project/overview.aspx

2. The **Fort Nelson project in British Columbia, Canada**, which will use CCS at a gas plant after amine separation of the CO_2 from the produced natural gas. Storage of CO_2 will be in a nearby saline formation. CO_2 injection is expected to begin in 2011 and ramp up to 1.2 to 2 Mt CO_2/year. http://www.netl.doe.gov/publications/proceedings/08/rcsp/factsheets/19-PCOR_Fort%20Nelson%20Demonstration_PhIII.pdf

3. Shell's **Quest project in Alberta, Canada**, which will store about 1 Mt CO_2/year captured at a hydrogen plant at its oil sands upgrader in central Alberta; injection is expected to begin in 2011. http://www-static.shell.com/static/ca-en/downloads/about_shell/what_we_do/oil_sands/quest-public-disclosure-v9.pdf

4. The **Redwater HARP project in Alberta, Canada**, which will store similar amounts of CO_2 captured at refineries, oil sands upgraders and chemical plants northeast of Edmonton, Alberta. Injection is expected to start in 2011 and ramp up to 1 Mt CO_2/year by 2015. http://www.arc.ab.ca/documents/Reef%20may%20hold%20key%20to%20large-scale%20carbon%20storage.pdf

5. The **WASP project in Alberta, Canada**, will capture CO_2 from one of the three TransAlta's coal-fired power plants in the area, using a chilled-ammonia process developed by Alstom. Injection is expected to start in 2011 or 2012. http://alberta.ca/home/NewsFrame.cfm?ReleaseID=/acn/200810/24549060A11EE-A487-6EAB-0BA6A4955D18D734.html

6. The **Zero-CO_2 plant in Germany**, which will use IGCC with pre-combustion capture technology at a 450 MW coal-fired power station and store the CO_2 in a saline formation. Power station operation is targeted for 2015, with storage beginning in 2020. https://www.rwe.com/web/cms/en/2688/rwe/innovations/power-generation/clean-coal/igcc-ccs-power-plant/

7. The **Husnes project in Norway**, a 400 MW coal-fired power station with post-combustion CO_2 capture and storage via EOR offshore in the North Sea. Project start-up is expected in 2010. http://sequestration.mit.edu/tools/projects/sargas_husnes.html
8. The **Karsto project in Norway**, a 420 MW natural gas plant which will use post-combustion capture technology and inject CO_2 offshore into a saline formation and/or for EOR. http://sequestration.mit.edu/tools/projects/naturkraft_karsto.html
9. The **Mongstad plant in Norway**, a 350 MW natural gas combined heat and power facility which will use post-combustion capture and store the CO_2 offshore in a geological formation. The plant is expected to start up in 2010, with full-scale operation in 2014. http://www.vattenfall.com/www/co2_en/co2_en/879177tbd/879231demon/879283demon/index.jsp
10. The **Masdar project in the United Arab Emirates**, a 420MW gas-fired power station with pre-combustion capture and storage of the CO_2 via EOR. Operation is expected by 2012. http://www.bp.com/genericarticle.do?categoryId=9024973&contentId=7046909
11. The **Ferrybridge project in the UK**, a 500 MW coal-fired power station retrofit with a supercritical boiler and turbine, and post-combustion capture. The CO_2 will be stored in a saline formation. Project operation is expected by 2011. http://sequestration.mit.edu/tools/projects/sse_ferrybridge.html
12. The **Hatfield project in the UK**, which will capture CO_2 from a 900 MW coal-fired power station for EOR in North Sea oilfields. Project operation is expected to begin after 2011. http://www.powerfuel.plc.uk/id10.html
13. The **Antelope Valley project in the USA**, a 120MW slipstream at a 450MW coal-fired electricity plant. The project will use post-combustion capture technology with ammonia. The CO_2 will be transported through an existing 330 km CO_2 pipeline and injected for EOR. Commercial operation is expected in 2012. http://sequestration.mit.edu/tools/projects/antelope_valley.html
14. The **Carson project in the USA**, a 390 MW project using IGCC at a petroleum coke plant to produce hydrogen. The CO_2 will be stored via EOR. The plant is expected to begin operation in 2014. http://sequestration.mit.edu/tools/projects/bp_carson.html
15. The **Northeastern project in the USA**, which will capture CO_2 from a 200 MW coal-fired power station fitted onto a 450 MW power station using post-combustion capture with chilled ammonia. The CO_2 will be stored via EOR. Operation is targeted for 2011. http://www.co2crc.com.au/demo/p_northeast.html
16. The **Tenaska project in the USA**, a 600 MW coal-fired plant using supercritical pulverised coal technology and CO_2 storage via EOR. Operation is anticipated in 2014. http://www.tenaskatrailblazer.com/
17. The **WA Parish Plant in the USA**, a 125 MW coal-fired power station, using post-combustion ammonia-based electrocatalytic oxidation technology for CO_2 capture. The CO_2 will be stored via EOR. The project is expected to be operational by 2012. http://sequestration.mit.edu/tools/projects/wa_parish.html
18. The **Wallula project in the USA**, using pre-combustion capture technology at a 600 MW IGCC coal-fired power station. CO_2 storage will be in basalt at a depth of 2 km. Site construction is due to begin in 2009, with operation by 2013. http://www.wallulaenergy.com/docs/ep_062007.pdf
19. The **Williston Basin project in the USA**, which will retrofit a 450 MW lignite-fired power station with post-combustion capture technology. The CO_2 is expected to be used for EOR. The project is expected to start in 2010. http://www.co2crc.com.au/demo/p_williston.html
20. The **Shell project in the Netherlands**, which will capture over 0.2 Mt /year of CO_2 from the hydrogen production unit at the Shell refinery near Rotterdam (Pernis); storage will take place in a nearby depleted gas field.

21. The **DSM/GTI project in the Netherlands**, which will capture over 0.2 Mt /year of CO_2 from DSM's ammonia production unit at the Chemelot site near Sittard-Geleen; storage will take place in chalksandstone layers (including coal layers) below the Chemelot site. http://www.gti-group.com/en/news/gti-wins-co2-storage-at-dsm
22. The **Buggenum IGCC project in the Netherlands**, where 1-2% of the produced syngas (representing about 2.5 MWe) will be captured in a side loop. http://www.clean-energy.us/success/buggenum.htm
23. The **SEQ oxyfuel project in the Netherlands**, where a 50 MWe gas-fired oxyfuel plant will be built and the captured CO_2 will be stored offshore in a depleted gas field.

2.4. Demonstration and Research Activities

As well as specific projects, there are a number of research and demonstration efforts worldwide relevant to CO_2 capture and storage which the CSLF will endeavour to coordinate activities with. These include:

1. The **IEA Greenhouse Gas R&D Programme**, which is a major international research collaboration that assesses technologies capable of achieving deep reductions in greenhouse gas emissions.
2. The **Intergovernmental Panel on Climate Change (IPCC)**, which provides an objective source of information about climate change initiatives through assessing on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic literature produced worldwide.
3. The **Global Carbon Capture and Storage Institute (GCCSI)**, which is being established to accelerate the deployment of CCS technology by supporting / initiating 20 fully integrated industrial-scale demonstration projects by 2020.
4. The **EU Zero Emissions Platform (ZEP)**, which aims to achieve 12 commercial-scale demonstration projects by 2020.
5. The **Near-Zero Emissions Coal (NZEC)** effort between the UK/EU and China, which aims to construct and operate a 450MW IGCC power station with pre-combustion capture and storage in a geological formation or through EOR by 2015.
6. The **UK CCS Competition**, which aims to award up to 100% funding to a full-scale CCS plant using post-combustion capture and offshore CO_2 storage. The intention is for the facility to be operational by 2014.
7. The **US CCS Effort**, which includes seven Regional Partnerships and aims to develop nine large-scale demonstration projects.
8. 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 offshore through a newly constructed infrastructure.
9. 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.
10. The **Alberta Provincial Government** in Canada announced in July 2008 a CCS fund of CAD 2 billion for large scale CCS implementation, from capture to storage ("cradle to grave"). Of the initial 54 applicants, 20 were asked to submit full proposals by the end of March 2009. Three to five CCS operations will be funded (will be announced in the fall of 2009), with the requirement to store at least 5 Mt CO_2 by the end of the funding period in March 2015.
11. The **Canadian federal government** announced in its January 2009 budget the establishment of a fund of CAD 850 million over five years for large-scale CCS demonstration projects.

MODULE 3: GAP IDENTIFICATION

The ultimate objective of CO_2 capture and storage R&D and demonstration activity is the development of safe and cost-effective processes for the capture, transport, and long-term storage of carbon dioxide to mitigate climate change impacts. In this module this broad objective is broken down into a number of more specific goals with respect to each particular technology. This is followed by a discussion of the gaps between current capabilities and what action would be required to meet these goals.

3.1. The Need for New/Improved Technology

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

- emission regulations or incentives to limit the discharge of CO_2 to the atmosphere; and
- cost reductions and/or appropriate financial incentives to reduce the financial burden of CO_2 capture and storage.

Although currently expensive, fossil fuel derived energy with CO_2 capture and storage is not necessarily more costly than other clean and renewable energy options such as solar or wind power (Figure 15). 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, separation technologies, or more radical approaches to the capture of CO_2 will be needed to accelerate deployment.

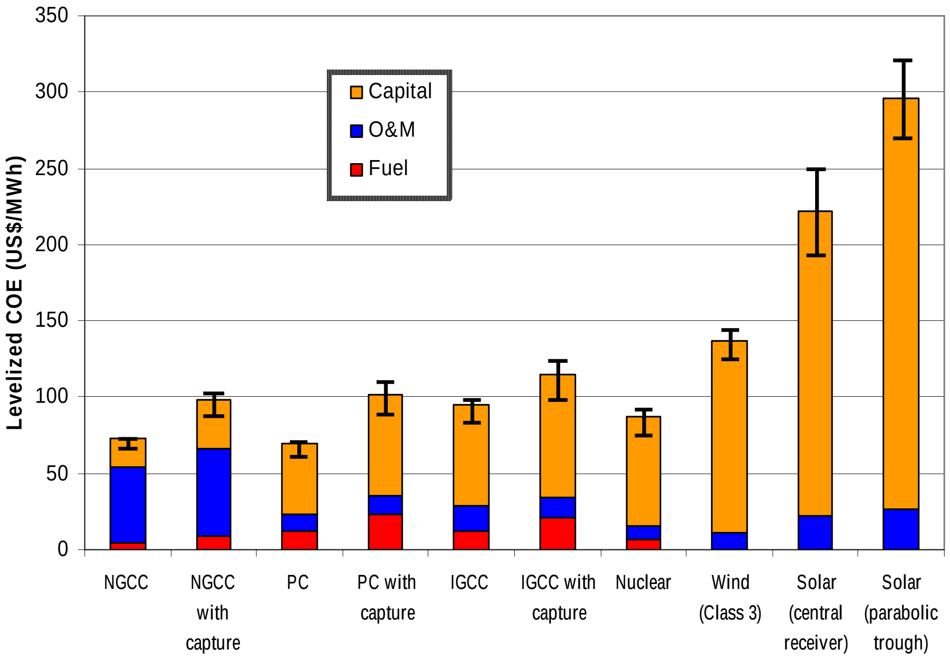


Figure 15. Comparison of CCS cost of electricity with other climate change mitigation technologies (courtesy of Electric Power Research Institute, 2008).

Relative to CO_2 capture, transmission costs are low and the technology problems are reasonably well understood. High pressure pipelines and/or ship tankers are the preferred modes of transportation of CO_2 in compressed liquid form. Transmission costs are, of course, distance dependent so the emission source should be located in close proximity to a storage site wherever possible. There is limited need for new technology in this area, although few, if any, tankers of the necessary capacity and fitness for purpose exist. In contrast, the sheer scope of creating major CO_2 pipeline transmission systems, some of which are likely to be located in populated areas, will raise legal, institutional and regulatory issues as well as public concerns.

The largest capacity for CO_2 storage is in geologic formations (deep saline formations, depleted oil and gas reservoirs, and unmineable coal seams) and the deep oceans. The primary issues are the difficult of quantifying actual storage capacity, long-term security, verifiability, and the environmental impact of storage.

Increased knowledge of the geology and geochemistry of proposed storage sites is needed. Improved monitoring and modelling techniques are necessary to verify storage, both for emissions trading and national accounting uses, and to prove long-term storage security. The environmental impact and safety of CO_2 storage needs to be understood better. Monitoring of naturally occurring CO_2 accumulations is also needed to provide information on levels of seepage and the behaviours of CO_2 in geological formations. It is necessary to demonstrate CO_2 capture and storage in several large-scale projects in order to optimise the technology and reduce costs, to establish expertise and industrial capability for the manufacture and installation of the plants, and to develop best practice guidelines.

Regulatory frameworks will also influence technical decisions. For example, national, regional and international laws and regulations will determine whether CO_2 is classified as a waste or not, whether impurities are acceptable in the stored CO_2 and whether international conventions, such as the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1972), should be amended to take climate change into account, as this problem was not envisaged at the time the conventions were framed (International Maritime Organisation, 2008).

Concerning the possible economies in the field of storage, a decrease of the drillings and casings price would have an unquestionable impact on the storage cost. Less expensive options of drilling, issued from geothermal or mining activities have to be analysed.

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. Public awareness and acceptance must be increased as public attitudes are a key factor influencing politicians and regulators.

Summary of key technological needs to assure widespread deployment:

1. Demonstrate, by 2020, fully-integrated industrial-scale CCS projects
2. Reduce CO_2 capture cost, efficiency penalties and transport infrastructure costs
3. Validate effectiveness of monitoring for safety, long-term security, environmental impact and verification
4. Establish applicable sets of operational guidelines for more accurate geological surveys and for injection/measurement/mitigation techniques
5. Create the ability to optimize transport infrastructures to accept CO_2 from different sources

3.2. Technology Gaps

3.2.1. 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 reduce the efficiency penalties associated with capture systems.

3.2.1.1 Post-combustion capture

The applicable technology for post-combustion capture is widely deployed in chemical processing. However, the gaps lie in transferring the technology to CCS specific applications, optimising capture systems for generation plant and industrial processes and addressing the economics of the capture process including the cost and performance of solvents.

Priority activities:

- ◊ Develop better solvents for CO_2 capture
- ◊ Identify optimal capture process designs and ways of integrating the capture systems with power stations to reduce energy loss and environmental impact
- ◊ Build understanding of both organic and inorganic non-precipitating absorption systems supported by pilot scale data (2-4 MW) for a selection of the most promising.
- ◊ Identify advantages and limitations of precipitating systems (e.g. carbonates).

3.2.1.2 Oxy-fuel

This technology is already used on an industrial scale but is currently very costly when applied to CCS. In order to address this key gap, priority activities should focus on technological advances, specifically in material science and in process engineering, that will reduce this cost and improve performance and reliability.

Priority activities:

- ◊ Develop high temperature turbines for gas-fired oxyfuel
- ◊ Develop CO_2/N_2 separation technology for industrial processes - blast furnaces
- ◊ Undertake R&D on material selections
- ◊ Research into CO_2 capture, compression and conditioning processes for oxy-fuel combustion
- ◊ Research into the economics and technical issues for the adaptation of cryogenic air separation units (ASU) in oxy-fuel power stations

3.2.1.3 Pre-combustion capture

Integrated Gasification Combined Cycle (IGCC) is the leading technology for pre-combustion capture. As an amalgam of several technologies, gaps exist in the effective integration of the key component technologies.

Priority activities:

- ◊ Undertake research into full process integration and optimization of the components for power station applications
- ◊ Develop better systems for coal gasification (e.g. higher efficiency shift processes), natural gas reformer and syngas cooler
- ◊ Improve CO_2 separation and capture technologies
- ◊ Develop high efficiency and low emission H_2 gas turbines

3.2.1.4 Emerging and new concepts for CO_2 capture

The emphasis here is on long-term exploratory R&D in advanced and innovative concepts for the next-generation of CO_2 capture technologies.

Priority activities:

- ◊ Conduct research in the following capture technologies:
  - Chemical looping
  - Post-combustion carbonate looping cycles
  - Gas separation membranes and adsorption processes for CO_2
  - Ion-transport membranes for O_2 separation

3.2.1.5 Improvements in generation efficiency

Recognising that CO_2 capture and compression equipment significantly reduces the available sent out electrical energy, there is a great need to improve power station efficiency. This is to reduce as far as possible the impacts of the additional plant loads due to capture technologies. Efficiency improvements extend to the design and integration of the CO_2 compression systems.

Priority activities:

- ◊ Support initiatives to improve efficiency of electricity generation plant
- ◊ Develop high efficiency gas turbines and support new cycle concepts
- ◊ Develop alternative power generation processes that have the potential to produce improved economics when paired with absorption capture

3.2.2. 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 which will present different regulatory, access and development challenges for different regions of the globe where CCS is to be implemented.

The key technical gaps include the costs associated with design and development of pipeline networks, pipeline integrity and safety, and suitable alternatives such as mobile transport systems. There are also other significant non-technology issues such as the economic and regulatory issues with establishing networks in dense population centres.

Priority activities:

- ◊ Conduct cost benefit analysis and modelling of CO_2 pipeline networks and transport systems for tankers and trucks
- ◊ Develop tanker transport of liquid CO_2
- ◊ 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
- ◊ Improve dispersion modelling and safety analysis for incidental release of larger quantities of CO_2 from the transport system (e.g. CO_2 pipeline, CO_2 ship or intermediate storage tank at harbor)
- ◊ Promote proper mitigation measures and design, to ensure safe establishment and operation of CO_2 pipelines through urban areas
- ◊ Identify and define proper safety protocols to protect CO_2 pipelines including response and remediation
- ◊ Identify regulations and standards that need addition or updating for CO_2 transportation (e.g. existing regulations for natural gas pipelines)

3.2.3. 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 unmineable coal seams. For CCS to be widely available for industrial-scale 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 CO_2/y or more per project) can be stored safely for millennia. This requirement applies particularly to deep saline formations and unmineable coal beds, as the storage capacity of oil and gas fields is relatively well defined and understood through oil and gas exploration and production.

Priority activities for all geological storage types:

- ◊ Develop best practice guidelines for storage site selection, operation and closure, including risk assessment and response and remediation plans
- ◊ Develop appropriate models to predict the fate and effects of the injected CO_2 (multi-phase fluid flow, thermo-mechanical-chemical effects and feedback), including leakage
- ◊ 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, and storage behaviour
- ◊ Assess long-term site security post-injection including verified mathematical models of storage
- ◊ Compile baseline surveys for measurement, monitoring and verification (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
- ◊ Define methods for the production and disposal of brine from saline formations as a result of CO_2 injection
- ◊ Address costs associated with storage, especially drilling and establishing wells

Specific priorities follow.

3.2.3.1 Deep saline formations

While deep saline formations are thought to have the largest potential capacity for CO_2 storage, better understanding of their storage capacity and geological, geomechanical and geochemical properties is required. Specific gaps include a lack of regional and site-specific knowledge about:

- The thickness and stability of the cap rock (its sealing potential);
- Reservoir formation depth, volume and characteristics;
- Trapping mechanisms and efficiency of storage;
- Long-term lateral transport and fate of brine (and consequently the CO_2), including pressure control and variation;
- CO_2 migration pathways and timeframes, and determining the volume of rock accessed by a migrating plume;
- The rate and effect of geochemical interactions between CO_2 and the reservoir formation mineralogy and fluids;
- Pressure building in the storage formation - consequences on storage capacity and on other activities using the same aquifer
- Remediation actions in case of diffuse CO_2 leakage far from the injection point or pollution of surrounding aquifers .

Priority activities:

- ◊ Conduct a comprehensive assessment of worldwide capacity for CO_2 storage in various geological settings but particularly deep saline formations that:
  - o Applies consistent methodology for storage capacity estimation
  - o Compiles, collates, and integrates existing aquifer capacity data from world-wide projects
  - o 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, petrophysics, hydrodynamics, geomechanics and so on)
  - o Provides tools for predicting spatial reservoir and cap rock characteristics, with assessment of uncertainties
  - o Provides a robust storage capacity classification system and informs the legal end of storage licensing procedures
- ◊ Produce a digital (GIS or 3D modelling package) world CO_2 storage atlas to cover all major geological storage types

3.2.3.2 Depleted oil and gas fields

Additional understanding of the geochemical reactions between CO_2 and the geological formation is required. The initial security of reservoirs (implicitly guaranteed by the presence of oil and/or gas) may be compromised by drilling, acid treatment, and fracturing during production. The integrity of abandoned wells (particularly very old or unknown wells) can be adversely affected by corrosion of the well casing and improper cementing, leading to leakage of CO_2 out of the formation. Over-pressurisation of the reservoir must be avoided in case existing faults are reactivated or new faults are created and the rate of injection adjusted and constantly monitored.

For depleted oil and gas fields, storage projects require site-specific evaluation of possible reservoirs to identify damage caused during hydrocarbon extraction and the status of existing, sealed or abandoned boreholes.

Priority activities:

- ◊ Develop best practice site selection and assessment guidelines
- ◊ Develop an inventory of oil and gas fields with large storage capacity

3.2.3.3 Unmineable coal seams

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 behaviour of coals in the presence of CO_2. Methods for improving the permeability of coals, such as the effectiveness and costs associated with fracturing, need to be assessed. Equally important is the realisation that the resource will be sterilised once it is used as a carbon dioxide sink.

Priority activities:

- ◊ Assess worldwide storage capacity in unmineable coal seams
- ◊ Research CO_2-coal interactions, especially with respect to the mechanisms of methane displacement and permeability decreases

3.2.3.4 Mineral Carbonation

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. Knowledge gaps are associated with the process for converting captured CO_2 into a mineral, for example, increases in the rate of reaction needed for practical storage. The environmental impacts of large-scale disposal of solid material also need to be examined.

Priority activities:

- ◊ Build on pioneer studies to further investigate the possibilities of enhancing mineral trapping of CO_2 and impurities in specific types of settings (basaltic and ultramafic aquifers, highly saline aquifers, geothermal reservoirs, etc.) and map these
- ◊ Study thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, geomechanics
- ◊ Carry out a techno-economical feasibility study relating to mineral storage of CO_2

3.2.4. Gaps in Uses of CO_2 (EOR and EGR)

Enhanced oil recovery (EOR), because of the economic benefit of the produced oil, provides the best practical near-term potential for CO_2 storage. Current practices, however, are optimised for oil recovery rather than CO_2 storage and the injected CO2 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 storage and oil recovery. The concept of enhanced recovery of gas (EGR) needs to be proven and shown to be beneficial in practice.

Enhanced coal bed methane (ECBM) production provides the opportunity for economic return in conjunction with CO_2 storage in coals. While it is known that CO_2 injection will cause the displacement of methane and its replacement with CO_2, greater understanding of the displacement mechanism is needed to optimise CO_2 storage and to understand the problem of decreased permeability of coals in the presence of CO_2 (see suggested project areas in 3.2.3.3.).

3.2.5. Gaps In Security of Geologic Storage

Site characterisation and monitoring prior to storage, 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 surveyed. 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 needed prior to injection. For monitoring and verification purposes, background information on CO_2 concentrations at ground level are needed as well as background information on seismic activity in the area.

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, must be available in the event of over-pressurisation. Methods of monitoring must be sufficiently sensitive to detect CO_2 concentrations only slightly above the background level, and at leakage rates of less than 0.1% per year. 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. Seismic activity should be monitored and compared to background levels.

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. Detailed mathematical models that have been verified will be important, especially during the post-injection period. Measuring leakage rates and migration of the CO_2 is important, not only from a safety and environmental point of view, but also to verify emission trading contracts and to provide evidence in legal disputes. All of these developments must recognise the length of time for which secure storage is required.

Risk assessment 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. Risk assessment techniques must be further developed and verified, which will require more field data, especially from monitored storage projects.

Priority activities:

- ◊ Model the fate and effects of injected or leaked CO_2
- ◊ Develop best practice guidelines on how to characterize and monitor a site prior to, during and after storage
- ◊ Build tools that can be used to characterise a potential storage site
- ◊ Develop low cost and sensitive CO_2 monitoring technologies
- ◊ Construct fail-safe procedures and guidelines for dealing with CO_2 leaks
- ◊ Create risk assessment tools to identify the likelihood and consequence of CO_2 leaks and inform effective decision making

3.2.6 CCS Integration Gaps

It is critical that broad integration of CCS is realised in new and retrofitted energy plants in order to gain the necessary experience and information through multiple large-scale demonstrations to meet the G8 goal of 20 demonstrations by 2020. Currently insufficient information exists on the design, cost, and space requirements, operation, and integration of CCS with energy facilities. This lack of information impedes making power stations and industrial plants, which are being designed and built today, CCS ready for when CCS technology achieves commercial status.

Priority activities:

- ◊ Incorporate the technical elements of CCS readiness into CSLF policy and technical documents
- ◊ Promote best practice approaches on the optimal design, costs, space requirements, operation and integration of CCS (CCS readiness) for existing power stations and infrastructure, industrial plants and new proposed projects

3.3 Summary of Key Technology Needs and Gaps

ELEMENT	NEED	GAPS
Capture	Reduce CO_2 capture cost and efficiency penalties	• Alternative absorption solvents or materials that reduce capture costs and increase energy efficiency compared with amine-based systems. • Alternative power generation processes that have the potential to produce improved economics compared with absorption capture.
Transport	Create the ability to optimise transport infrastructure to accept CO_2 from different sources; reduce transport infrastructure costs	• Understanding of the effects of CO_2 impurities on CO_2 transport. • Modelling capability to optimise transport network of CO_2 between sources and potential sinks. • Response and remediation procedures developed in advance of the possibility of CO_2 pipeline accidents.
Storage	Demonstrate sufficiency of CO_2 storage capacity; validate monitoring for safety, long-term security, environmental impact and verification	• A comprehensive global storage atlas (e.g. GIS) of suitable geological formations with information on emission sources and other relevant details. • Understanding of CO_2 storage capacity and geological, geomechanical and geochemical properties of deep saline formations. • Understanding CO_2-coal interactions, especially with respect to the mechanisms of methane displacement and permeability changes. • Site-specific information on CO_2 background concentration and seismic activity. • Capability of ensuring long-term site security post-injection including verified mathematical models of storage. • Instruments capable of measuring CO_2 levels close to background and to distinguish between CO_2 from natural processes and that from storage. • Best practice guidelines for storage site selection, operation and closure, including risk assessment. • Site-specific evaluation of reservoirs and oil/gas fields to identify damage due to hydrocarbon extraction and status of sealed boreholes. • Development of response and remediation plans on a site-specific basis prior to injection.
Integration	Demonstrate 20 fully-integrated industrial-scale CCS projects by 2020.	• Information on the design, cost, operation, and integration of CCS with energy facilities and industrial processes. • Promotion and understanding of “CCS-ready” systems for major energy and industrial assets. • Consistent information on existing projects.

MODULE 4: TECHNOLOGY ROADMAP

4.1. The Role of the CSLF

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

4.2. Achieving Wide-Spread CCS Deployment

This roadmap is intended to help set priorities for the CSLF by identifying key topics that need to be addressed to achieve the goal of wide-spread deployment of CCS. Module 1 has briefly described the current status of carbon dioxide capture and storage technologies. Module 2 has highlighted the global progress made on CCS and Module 3 has identified the needs and technology gaps to help guide this revision of the roadmap. Module 4 is the Technology Roadmap which has been updated to address the identified gaps.

The focus of the Technology Roadmap is on:

- Achieving commercial viability and integration of carbon dioxide (CO_2) capture, transport and storage technologies;
- 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.

Since the original Roadmap was developed in 2004 (Figure 14) there has been significant activity and progress made in all aspects of CCS, resulting in successful completion of the early milestones identified in the timeframe 2004-2009. For example, there are now 20 recognised CSLF projects demonstrating worldwide collaboration on CCS and contributing to the CCS knowledge base. Much has been learned that allows the future path forward to a post 2020 timeframe to be identified. However there are still a number of important gaps that need to be addressed and where it is necessary to encourage projects at the R&D and pilot level in addition to the much needed large integrated demonstration projects.

In all aspects, effective sharing of knowledge and lessons learned will be a key element that will contribute to the acceleration of deployment of CCS. To assist this, it will be beneficial to establish guidelines on the type and level of information to be shared that could be applied worldwide. This would help to avoid problems with sharing of information between countries and regions and so undoubtedly facilitate the global take-up of CCS.

The updated Roadmap reflects those challenges that need to be addressed as well as milestones that need to be achieved in order to realise wide scale deployment of CCS post 2020. It is summarised in Figure 17, which now encompasses two additional key issues: CCS integration and CO_2 transport infrastructure.

ELEMENT	NEED	2009-2013	2014-2020	Post 2020
Capture	Reduce CO_2 capture cost and efficiency penalties	• Research and develop scalable low-cost capture technologies	• Demonstrate at large-scale advanced, affordable capture systems	• Commercial capture technologies available
Transport	Create the ability to optimise transport infrastructure to accept CO_2 from different sources; reduce transport infrastructure costs	• Determine allowable CO_2 impurities on CO_2 transport • Establish models to optimise transport network of CO_2 between sources and potential sinks	• Establish technical standards for trans-boundary CO_2 transport • Establish regional networks as examples of multiple source CO_2 transportation	• Establish infrastructure emplacement for CO_2 transport
Storage	Demonstrate sufficiency of CO_2 storage capacity; validate monitoring for safety, long-term security, environmental impact and verification	• Develop a global atlas of CO_2 storage capacity • Establish methodologies for estimating site-specific and worldwide storage capacity • Establish methodologies for risk assessment • Initiate large-scale field tests for injection and MMV • Establish industry best practices guidelines for reservoir selection, CO_2 injection, storage, and MMV	• Refine global atlas of CO_2 storage capacity • Successfully complete large-scale field tests for validation of injection and MMV best practices for updating industry standards • Commercialise MMV technologies	• Implement commercial operation of storage sites
Integration	Demonstrate, by 2020, fully-integrated industrial-scale CCS projects	• Initiate large-scale and commercial demonstration projects • Establish guidelines on the design, cost, operation and integration of CCS including protocols for CCS readiness • Build a comprehensive CCS projects database	• Establish operational experience and lessons learned with CCS • Demonstrate integrated next generation technologies	• Achieve commercial readiness through successful demonstrations

Figure 17. 2009 CSLF Technology Roadmap

4.3 CSLF Actions

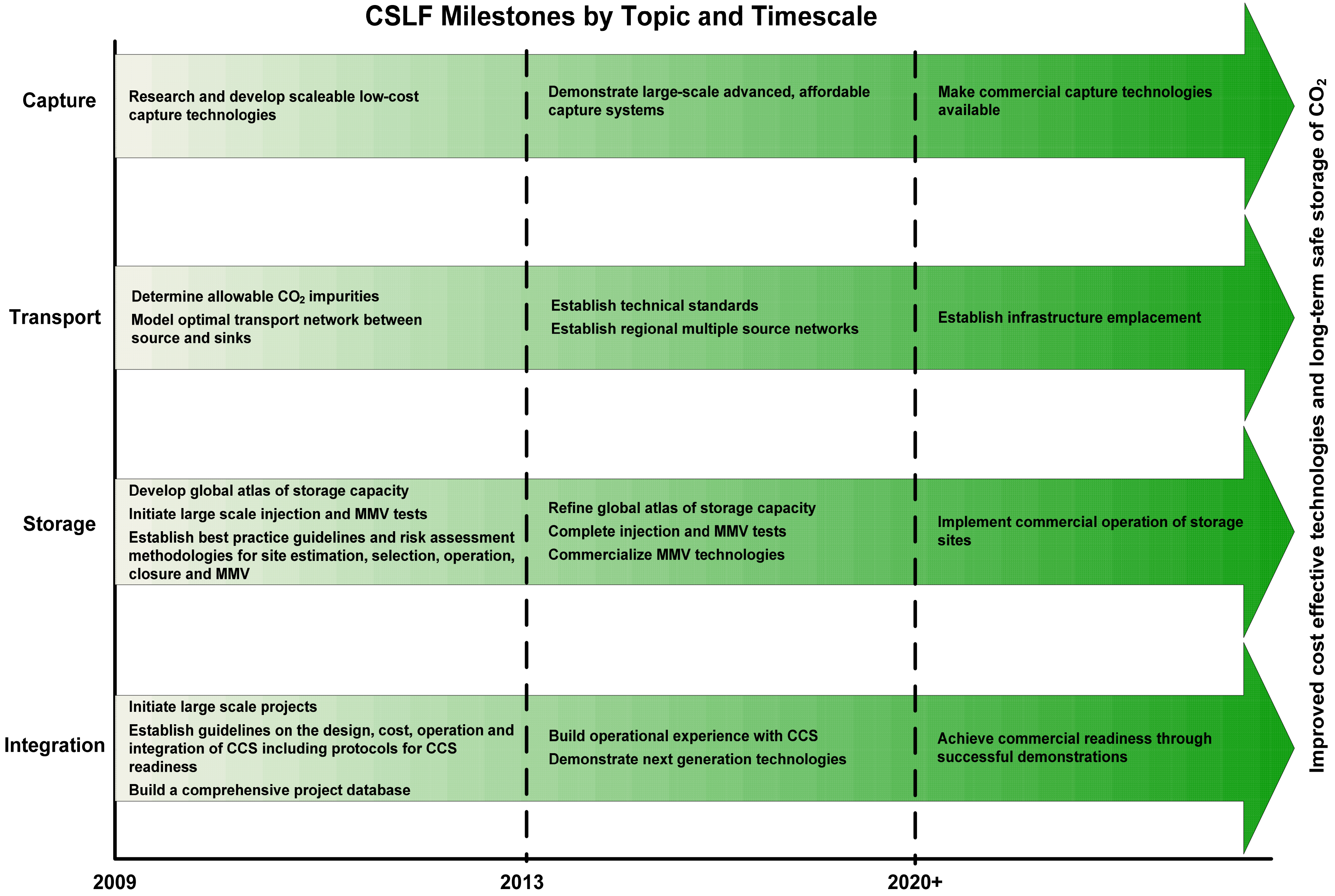
Through its activities, engagement with members and the development of key resources such as this Roadmap, the CSLF has been instrumental in stressing the importance of CCS as an indispensable technology in a set of measures to address climate change. The support by governments, industry and the general community for urgent measures is intensifying and there is a great need to implement large scale projects as soon as possible with wide deployment by the target date of 2020.

At the time of writing, the Global Financial Crisis (GFC) has placed a significant constraint on capital. For the CCS industry the consequences of the GFC are significant threats to research, development and demonstration of large scale projects. However, it could also provide opportunities. One indication of this is the number of governments that have announced significant funding for CCS infrastructure projects as part of economic stimulus packages. As a result of this economic environment, the CSLF must continue to actively work with governments to harvest support and to ensure that a coordinated approach is taken to addressing all immediate technology gaps and priorities. Knowledge sharing will be a key element of such an approach.

Key among the project groupings is an increasing emphasis on:

- Initiating integrated, large scale and commercial demonstration projects;
- Identifying, assessing and preparing safe storage sites;
- Building best practice guidelines, standards, methodologies and setting up information flows across all aspects of carbon dioxide capture, transport, storage and integration; and
- Reducing the costs of capture through improved processes and research into alternatives.

While the technical challenges are appreciable, there are also major regulatory, financial and community-perception hurdles for CCS to overcome in order for it to be widely deployed as soon as practical. The CSLF is not alone in confronting these vital, challenging tasks. In partnership with organisations such as the IEA and the GCCSI, the CSLF can marshal a range of resources to deploy critical technologies and to address these other barriers. Figure 18 summarises the key milestones for the CSLF.



CSLF Milestones by Topic and Timescale

	2009	2013	2020+
Capture	Research and develop scaleable low-cost capture technologies	Demonstrate large-scale advanced, affordable capture systems	Make commercial capture technologies available
Transport	Determine allowable CO_2 impurities Model optimal transport network between source and sinks	Establish technical standards Establish regional multiple source networks	Establish infrastructure emplacement
Storage	Develop global atlas of storage capacity Initiate large scale injection and MMV tests Establish best practice guidelines and risk assessment methodologies for site estimation, selection, operation, closure and MMV	Refine global atlas of storage capacity Complete injection and MMV tests Commercialize MMV technologies	Implement commercial operation of storage sites
Integration	Initiate large scale projects Establish guidelines on the design, cost, operation and integration of CCS including protocols for CCS readiness Build a comprehensive project database	Build operational experience with CCS Demonstrate next generation technologies	Achieve commercial readiness through successful demonstrations

Improved cost effective technologies and long-term safe storage of CO_2

Figure 18. A summary of the key milestons and Technology Roadmap for the CSLF in 2009

4.4 Summary

This Roadmap 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 the development of improved cost-effective technologies for the separation, capture, transport and long-term storage of carbon dioxide.

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.

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 by 2020 and deployed post 2020. It is essential to establish the technical foundation for affordable capture, transport, and safe and effective long-term geologic storage of CO_2 as quickly as possible.

The CSLF will continue to catalyse 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 Technology Roadmap. The CSLF will continue to work with existing and new support organisations, such as the Global Carbon Capture and Storage Institute, in order to efficiently utilise scarce world resources and effort and to ensure that key technology gaps are addressed.

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