CSLF-T-2004-10
August 30, 2004

CARBON SEQUESTRATION LEADERSHIP FORUM

Technical Group

Carbon Sequestration Leadership Forum
Draft Technology Roadmap

Note by the Secretariat

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Final Draft Technology Roadmap

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Background

At its inaugural CSLF meeting in June 2003, the Technical Group tasked the Secretariat with the development of a Technology Roadmap. The purpose of this Technology Roadmap is a guide for the CSLF and its Members that will describe possible routes to future CO_2 capture, transport and storage needs. A draft of the Roadmap was prepared by the Secretariat and was circulated for review by CSLF Members prior to the second CSLF meeting, in January 2004 in Rome, Italy. At that meeting the Technical Group decided that an extensive rewrite of the Roadmap was necessary and was to be based on a framework developed by the United Kingdom. Based on the United Kingdom's framework, the Secretariat and the United States drafted Modules 0 and 4, while the United Kingdom with assistance from the International Energy Agency drafted Modules 1-3. Comments on these modules were obtained from Technical Group delegates, and an ad hoc Technical Group meeting was held in Salvador, Brazil on August 20, 2004, to develop a final draft.

Action Requested

The Technical Group is requested to recommend approval of the final draft Technology Roadmap to the Policy Group.

Conclusions

The Technical Group is invited to note in the Minutes of its meeting of September 13, 2004 that:

> "The Technical Group recommended approval of the final draft CSLF Technology Roadmap to the Policy Group."

CARBON SEQUESTRATION LEADERSHIP FORUM

Draft Technology Roadmap

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MODULE 0: INTRODUCTION

0.1. Mission Statement

The Carbon Sequestration Leadership Forum (CSLF) is a Ministerial-level international initiative that is focused on development of improved cost-effective technologies for the separation and capture of carbon dioxide (CO_2) for its transport and long-term safe storage. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical issues, as well as economic, and environmental challenges. The CSLF will also promote awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

0.2. The CSLF Technical Group and Its Role

The CSLF consists of a Policy Group, a Technical Group, and a Secretariat. The Policy Group governs the overall framework and policies of the CSLF and is responsible for dealing with key legal, regulatory, financial, public perception, institutional-related or other issues associated with the achievement of improved technological capacity. The Secretariat acts administratively as principal coordinator of activities and communications for the CSLF. The actual development and deployment of CO_2 capture, transport and storage technologies is under the purview of the CSLF Technical Group.

Specifically, the role and responsibilities of the Technical Group are:

- Identify key technical, economic, environmental and other issues related to the achievement of improved technological capacity;
- Identify potential areas of multilateral collaboration on CO_2 capture, transport and storage technologies;
- Foster collaborative research, development, and demonstration (RD&D) projects reflecting CSLF Members' priorities;
- Assess regularly the progress of collaborative projects and make recommendations to the Policy Group on the direction of such projects;
- Establish and regularly assess an inventory of the potential areas of needed research;
- Facilitate technical collaboration with all sectors of the international research community, academia, industry, government and non-governmental organizations; and
- Consider approaches to address issues associated with the above functions.

The Technical Group also tracks the progress of development and deployment of CO_2 capture, transport and storage technologies. One of the tools needed for doing this is a Technology Roadmap.

0.3. The Purpose of the CSLF Technology Roadmap

Individual technical issues must be addressed and overcome if the CSLF is to fulfill its mission. These include:

- Achieving cost reduction for CO_2 capture, transport and storage technologies;
- Developing an understanding of global storage potential;
- Matching CO_2 sources with potential storage sites;
- Demonstrating the effectiveness of CO_2 storage; and
- Building technical competence and confidence through multiple demonstrations.

The pathway toward commercial deployment of CO_2 capture, transport and storage technologies over the next decade is sure to have many twists and turns. This Technology Roadmap is intended to facilitate this effort. Included are modules that describe the current status of these technologies, ongoing activities in CO_2 capture, transport and storage, and identification of technology gaps and non-technology needs that should be addressed over the next decade. The final module in this Technology Roadmap is the roadmap itself, which describes various approaches toward CO_2 capture, transport and storage that individual CSLF Members could utilize and indicates achievable milestones between now and 2013.

The purpose of this Technology Roadmap is therefore as a guide for the CSLF and its Members that will describe possible routes to future CO_2 capture, transport and storage needs. It will indicate areas where the CSLF can make a difference and add value through international collaborative effort. It will assist the CSLF in achieving its mission.

MODULE 1: CURRENT STATUS OF CO_2 CAPTURE AND STORAGE TECHNOLOGY

1.1. CO_2 Capture

CO_2 is emitted to the atmosphere in the flue gases of power stations and industrial plants such as blast furnaces and cement kilns, from the commercial and residential sectors that use fossil fuels for heating, from agricultural sources, and from automobiles and other mobile sources. This document concentrates on power station emissions, and discusses CO_2 capture from other sources only briefly. A typical coal-fired 500MW_e power station will emit about 400 tonnes/hour of CO_2 in the flue gas containing about 14% CO_2 (by volume), while a modern natural gas-fired combined cycle (NGCC) plant of the same size will emit about 180 tonnes/hour of CO_2 in the flue gas containing about 4% CO_2. It is therefore necessary to separate the CO_2 from the flue gas so that essentially pure CO_2 is available for storage.

CO_2 capture is, at present, both costly and energy intensive. Costs depend on the type and size of plant as well as the type of fuel used. CO_2 capture systems may conveniently be divided into three categories: 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 natural gas combined cycle power station with post-combustion capture of CO_2.

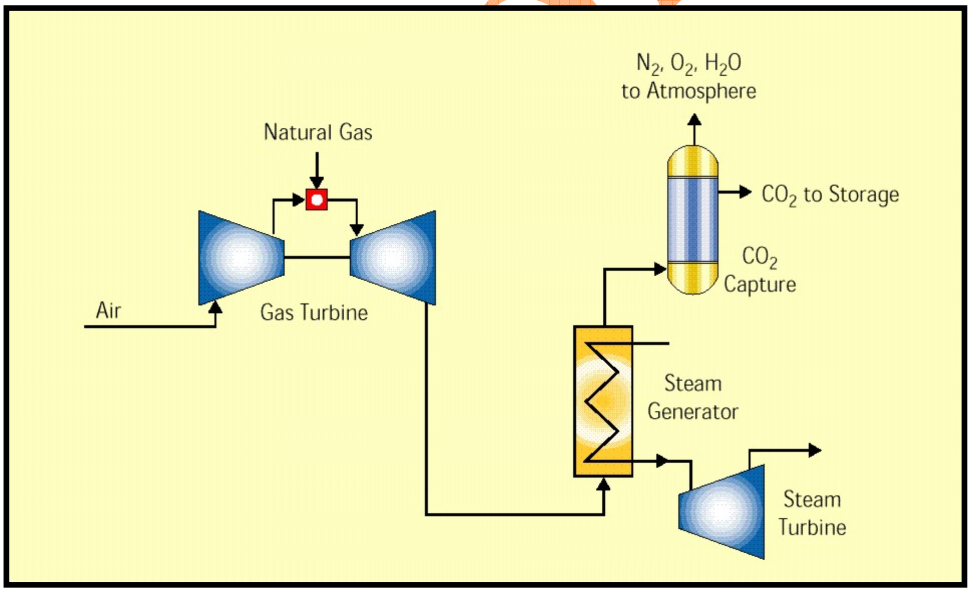

Figure 1. Gas turbine combined cycle with post-combustion capture of CO_2 (courtesy of the IEA Greenhouse Gas R&D Programme).

Post-combustion capture can also be applied to coal-fired power stations but additional measures are needed to prevent the impurities in the flue gas from contaminating the CO_2 capture solvent. Two particular disadvantages of this approach are the large volumes of gas which must be handled, resulting in large equipment and high capital costs, and the amount of energy used.

1.1.2. Pre-combustion Capture

Increasing the CO_2 concentration would reduce equipment size and allow different solvents having lower regeneration energy requirements to be used. This can be achieved by pre-combustion capture. In this approach the fuel is first partially reacted at high pressure with oxygen or air and, in some cases, steam, to produce mainly 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 the H_2 is used as fuel in a gas turbine combined cycle plant. Figure 2 is a simplified diagram of a coal-fired integrated gasification combined cycle (IGCC) power plant with pre-combustion capture of CO_2. The initial coal reaction stage is known as gasification. Although pre-combustion capture involves a more radical change to the 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 can be burned in an existing gas turbine with little modification, this technology has not been demonstrated. At least two large gas turbine manufacturers are known to have undertaken tests to establish criteria for the combustion of H_2-rich fuels. Current practice would be to dilute the H_2 with nitrogen (N_2).

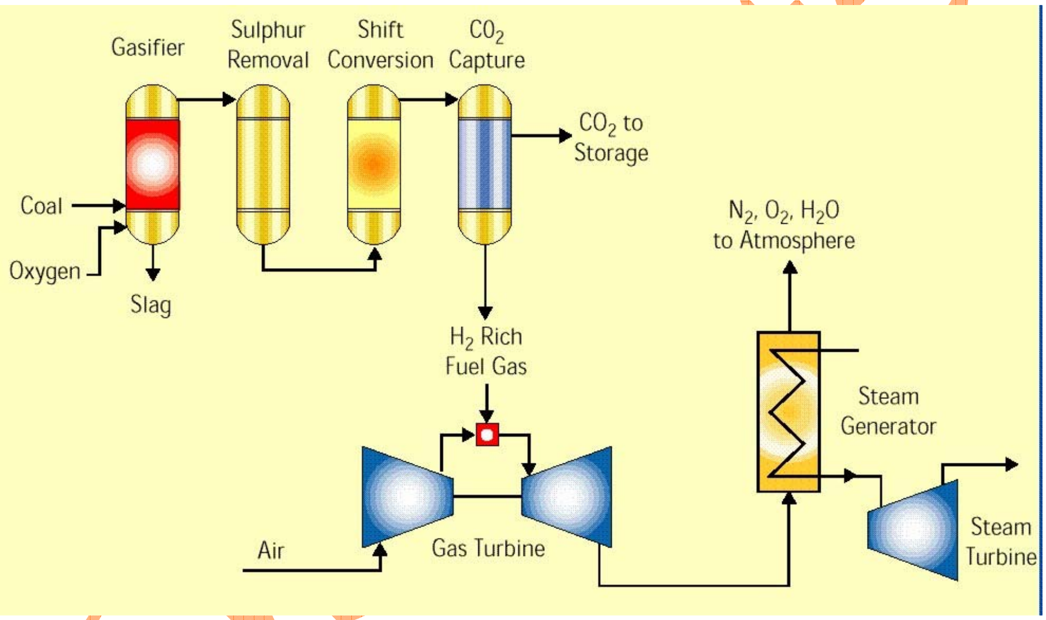

Figure 2. Coal-fired IGCC with pre-combustion capture of CO_2 (courtesy of the IEA Greenhouse Gas R&D Programme)

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, for example in the steel industry. 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 is highly concentrated in 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 in small scale test rigs.

1.1.4. Type of Capture Technology

Several different technologies can be used in these systems to separate CO_2 from a gas stream. Some of the most widely used ones 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. The CO_2 reacts with the solvent in the 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 established 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 oxidizing gases such as flue gas. The largest unit operating on oxidizing gas, at Trona, California, USA, captures 800 tonnes/day of CO_2, which is about 10% of the scale required for a 500MW coal-fired power plant.

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 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. Physical solvents, which combine less strongly with CO_2, may be preferable in pre-combustion capture. The physical solvents have a larger CO_2 capacity at pre-combustion conditions and CO_2-solvent separation can be accomplished by reducing the stripper pressure, resulting in lower regeneration energy consumption. Physical solvent processes suitable for CO_2 capture are the Rectisol, Selexol, and Fluor processes. Physical solvent scrubbing of CO_2 is well established, e.g. in ammonia production plants.

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. In pressure swing adsorption (PSA), regeneration is accomplished by reducing pressure, while in temperature swing adsorption (TSA) the adsorbent is regenerated by raising its temperature. Another approach is electric swing adsorption (ESA), where regeneration takes place by passing a low-voltage electric current through the adsorbent. PSA and TSA are commercially practised and are used to some extent in hydrogen production and in removal of CO_2 from natural gas. ESA is not yet commercially available. Adsorption 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 can be used to separate one component of a gas mixture from the rest. Currently available membrane materials include porous inorganics, nonporous metals (e.g. palladium), polymers and zeolites. Many membranes cannot achieve the high degrees of separation needed in a single pass, so multiple stages and/or recycle of one of the streams are necessary. This leads to increased complexity, energy consumption and costs. Suitable membranes could be used to separate CO_2 at various locations in power generation processes, for example from fuel gas in an IGCC process or during combustion in a gas turbine.

The solvent-assisted membrane combines 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 the energy required to achieve the low temperatures. 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

The need to capture CO_2 may make some radically different power generation technologies attractive. One possible 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. The gas product from the second reactor contains only O_2-depleted 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.

Other concepts are under investigation.

1.1.5. The Effect of Fuel Type

The presence of fuel contaminants, particularly from coal, may impose additional constraints on the choice and operation of CO_2 control technology. Potential particulate problems include erosion of turbine blades in the IGCC process, contamination of solvents and fouling of heat exchangers in absorption processes, and fouling of membranes or sorbents in one of the new capture processes. Sulphur and nitrogen compounds must also be reduced to low levels upstream of 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 decrease the separation or capture efficiency. In contrast, natural gas and its combustion products are much more benign and should create fewer problems for all potential CO_2 capture options.

1.1.6. Retrofit Application

The techniques described above could be applied, in principle, in existing as well as in new plants. New plants would have higher efficiency, be more easily adapted and have longer life.

However, many plants, especially coal-fired power plants, continue to be used 30 years or more after construction. In the USA, projects for re-powering existing coal plants have produced much extended lifetimes and, in some cases, substantially improved efficiencies. This suggests that owners might be interested in retrofitting CO_2 capture to an existing plant in some cases. Local conditions will be an important factor in determining whether retrofit is implemented. Retrofitting gas-fired plants might be more attractive in two respects - the average age of gas-fired plants is less than that of coal-fired plants and the efficiency is higher.

1.1.7. Other Sources of CO_2

The electric power industry is responsible for just over one-third of all emissions of CO_2 from combustion of fossil fuels. The emissions from other, large industrial sources, including iron and steel production, natural gas processing, petroleum refining and petrochemical processing, cement manufacture, amount to about 25% of the total. As the CO_2 emitted from such processes is typically contained in a few large process streams, similar to fuel-fired power generation, it should be possible to apply capture of CO_2 here as well. The high CO_2 concentrations of some of these streams may provide opportunities for early application of CO_2 capture technology.

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 expensive, storage in vehicles would be an added burden, and collection and transportation of CO_2 from many small sources would suffer from diseconomies of (small) scale. 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. Some aspects of this are discussed below.

1.1.8. Hydrogen Production

Commercial production of H_2 currently involves synthesis from fossil fuels in a multi-step process similar to that described in 1.2. Addition of CO_2 capture and storage technology would require a relatively small change to the process, so production of H_2 from fossil fuels may help make the transition to an energy system which makes greater use of H_2 as an energy carrier. Further improvements of the process are possible.

1.1.9. Further Work Required

As will be discussed later, the capture step is the most important in determining the overall cost of CO_2 capture and storage. Incremental decreases in the cost of solvent absorption systems are regularly reported; many ideas have also been proposed for new separation systems, new ways of deploying existing separations, and new plant configurations to make capture easier and less costly. However, it is not clear at present that any of these schemes offer radical reductions in the cost of capture. It seems likely that 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[1] to a long term storage site. In principle, transmission may be accomplished by pipeline, tankers, trains, trucks, compressed gas cylinders, as a CO_2 hydrate, or as solid dry ice. However, only pipeline and tanker transmission are reasonable options for the large quantities of CO_2 associated with, for example, a 500MW power station. Trains and trucks could be used in the future for the transport of CO_2 from smaller sources over short distances.

1.2.1. Pipelines

Dry CO_2 is inert and relatively easily handled. CO_2 transmission by pipeline began several decades ago. About 30 million tonnes per year of CO_2 are currently transmitted through about 3000km of high pressure CO_2 pipelines, mainly in North America. Most of the CO_2 is obtained from natural underground sources and is used for enhanced oil recovery. 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, would be built, if CO_2 capture and storage became widely used.

1.2.2. Ship Tankers

Ships are now used on a small scale for the transport of CO_2. Large scale transport of CO_2 from power stations located near appropriate port facilities may occur in the future. The CO_2 would be transported as a pressurised cryogenic liquid, for example at approximately 6 bar and -55˚C. Ships offer increased flexibility in routes, avoid the need to obtain rights of way, and they may be cheaper, particularly for longer distance transportation. Ships similar to those currently widely used for transportation of liquefied petroleum gas (LPG) and liquefied natural gas (LNG) could be used to transport CO_2.

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[1] In this paper, the word "transmission" will be 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.

1.3. Storage of CO_2

1.3.1. General Considerations

CO_2 storage must have low environmental impact and reasonable cost. It must conform to appropriate national and international law, and it must achieve the confidence of the public. Technology must be developed to verify the integrity of the storage site.

1.3.2. Geologic Storage

Most of the world's carbon is held in geologic formations. CO_2 may potentially be stored in deep saline formations, in depleted oil and gas reservoirs, and in unminable coal beds as shown in Figure 3. Each method possesses unique advantages and disadvantages, and the capacities of the reservoirs are widely different.

1.3.2.1. Deep Saline Formations

The largest option for geologic storage is provided by deep saline formations. Such formations are unsuitable as potable water supplies because of their salinity, and must be suitably isolated from potable aquifers to prevent cross-contamination. The total CO_2 capacity of these formations, while highly uncertain, is sufficient to store many years of CO_2 production. Suitable saline formations should have sufficient permeability to allow large volumes of CO_2 to be injected and should have a low permeability cap rock to prevent CO_2 leakage. A portion of the injected CO_2 will dissolve in the saline water where it will slowly react with the formation to produce mineral carbonates, thereby producing truly permanent storage of the CO_2.

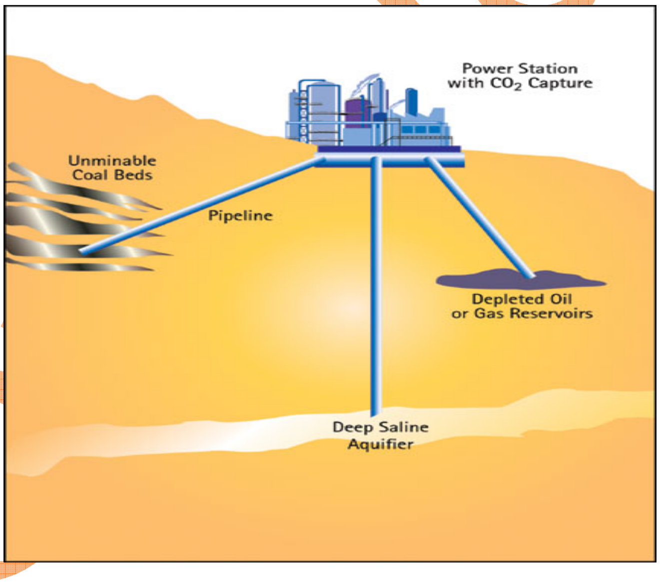


Figure 3. Geologic storage options (courtesy of the IEA Greenhouse Gas R&D Programme)

The Sleipner project in the Norwegian sector of the North Sea is the first demonstration of CO_2 storage in a deep saline formation designed specifically for climate change mitigation purposes. Injection of roughly one million tonnes per year of CO_2 captured from a natural gas stream began in 1996. The CO_2 is injected at a depth of about 1000m and is being monitored and modelled in an international project established by Statoil with the IEA Greenhouse Gas R&D Programme.

1.3.2.2. Depleted Oil and Gas Reservoirs

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. The reservoirs are composed of permeable rock formations with impermeable cap rock. The original integrity of the reservoirs is guaranteed as they trapped oil and gas for millions of year. Care must be taken, however, to ensure that past operations have not damaged the reservoir in the vicinity of the wells, and that the seals of shut-in wells remain intact. Costs should be reasonable as the sites have already been explored, their geology is reasonably well known, and there is potential to use some of the oil and gas production equipment for the CO_2 injection.

Perhaps the most significant difference between depleted oil and gas reservoirs is that all oil reservoirs contain unproduced oil after production has ceased. CO_2 injection should trigger additional production which may help offset the cost of CO_2 storage. In this sense, storage in depleted reservoirs will involve an element of enhanced oil recovery (EOR). CO_2 injection in depleted gas reservoirs, in contrast, will not, in many cases, result in new production.

1.3.2.3. Unmineable Coal Beds

CO_2 injected into unmineable coal beds will be adsorbed by the coal and stored as long as the coal is not mined or otherwise disturbed. Methane, which is naturally present in many unmineable coal beds, will be displaced when CO_2 is injected. Enhanced coal bed methane production, as this process is known, is discussed in the following section on uses of CO_2. One of the major problems concerning injection is the variable, and sometimes low, permeability of the coal. Coal tends to swell in contact with CO_2 which will reduce the permeability still more. Low permeability can, in some cases, be overcome by fracturing the formation.

Storage in unmineable coal beds may be theoretically feasible, but it must be proven to be widely applicable.

1.3.3. Deep Ocean Storage

Two broad methods of ocean CO_2 injection have been considered. 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. However, in reality, the capacity will be determined by environmental considerations.

In the study of ocean injection, near-field effects, i.e., environmental effects near the point of CO_2 injection, are of primary concern.

1.3.4. Mineralization

Nature's way of geologically storing CO_2 is the very slow reaction between CO_2 and naturally occurring minerals, such as magnesium silicate, to form the corresponding mineral carbonate. 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 removed from the atmosphere essentially forever. 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 other storage options under consideration.

1.3.5. Other Storage Options

A number of additional CO_2 storage options are being considered including injection into basalt, oil shale, salt caverns, geothermal reservoirs, and lignite seams, as well as methanogenesis in coal seams or saline formations. All are in early stages of development, and generally have limited capacity. They may in the future, however, provide niche opportunities for emissions sources located far from the more traditional storage options.

1.4. Uses for CO_2

If there is demand for CO_2, some or all of the costs may be offset by sales of CO_2. The total quantity of CO_2 that could be used will, ultimately, be swamped by the quantity that could be captured but some uses may provide openings for initial demonstrations of CO_2 capture processes, a necessary step in the further development of this technology.

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

Conventional oil production techniques recover only about 30% of the original oil in the reservoir. With secondary recovery techniques, principally water flood, recovery rates of 60-70% can be reached. Tertiary recovery can be used to recover even more of the oil. One of the tertiary techniques is CO_2 injection, which is already used in several parts of the world. At present most of the CO_2 used for enhanced oil recovery is obtained from naturally occurring formations while some is recovered from natural gas production. The CO_2 left in the reservoir at the end of production can be considered stored, just as would be the case if it had been injected primarily for storage. In 2000, there were 84 EOR projects worldwide using CO_2.

The Weyburn project, in which CO_2 captured from a coal gasification project in North Dakota, USA is transported 180 miles to an EOR site in Saskatchewan, Canada, is the first major project designed to demonstrate the long-term effectiveness of CO_2 capture coupled with enhanced oil recovery.

Enhanced gas recovery is somewhat different. Injection of CO_2 into a producing gas reservoir will help maintain reservoir pressure and increase the rate of gas production. After a certain period, breakthrough will occur and CO_2 will be produced along with the gas. 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.

1.4.2. Enhanced Coal Bed Methane (ECBM) Production

CO_2 injected into methane-containing coal beds will preferentially displace adsorbed methane, thereby increasing methane production. The CO_2 that is adsorbed in place of the methane is thereby permanently stored. Coal will adsorb about twice as much CO_2 by volume as methane.

The first CO_2 enhanced coal bed methane project has been operating in New Mexico, USA for a number of years, and a field test facilitated by the IEA Greenhouse Gas R&D Programme is now being carried out by the Alberta Research Council. A third demonstration project is just starting in Poland.

1.4.3. 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. Although, none of this CO_2 is sequestered, it has been recognised in the Netherlands that captured CO_2 could be used to avoid burning fossil fuel for this purpose, in which case there would be climate mitigation benefits.

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; if these are used to avoid the burning of fossil fuels, there would be climate benefits. The CO_2 could come from flue gases. The demand for high value products is insufficient to justify large-scale capture of CO_2 and, anyway, the carbon is fixed for only a short time (the lifetime of the product).

1.4.4. Industrial Products

CO_2 is thermodynamically stable so that use as a chemical raw material will require significant energy input. In addition, the total quantity of CO_2 produced by fossil fuel combustion is so large that potential uses are dwarfed in comparison. Nevertheless, there are currently cases in which power stations and industrial plants sell captured CO_2.

CO_2 captured from ammonia (NH_3) reformer flue gas is now used as a raw material in the fertilizer industry for the manufacture of urea. In addition, 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. The mitigation benefits of any chemical use of CO_2 must be examined carefully to ensure that emissions associated with the energy used in the process will offset the reductions achieved by using captured CO_2.

1.5. The Potential for CO_2 Storage

As pointed out above, in enhanced oil recovery and enhanced coal bed methane production, CO_2 injection can generate income, although this may be insufficient to offset fully the cost of capture. Nevertheless, such approaches may provide early opportunities for demonstrating CO_2 storage. Once the more profitable situations have been exploited, the storage of CO_2 will depend on other means of covering the costs, such as emissions trading. Storage of CO_2 in oil and gas reservoirs will benefit from the fact that the geology of the reservoir is reasonably well known and existing equipment may sometimes be adapted for CO_2 injection. The same does not apply to unmineable coal seams since there is less knowledge about the geology, and surface facilities and equipment are not available for re-use. Storage in deep saline formations does not generate a by-product to offset the costs so the full cost of any project must be justified for reasons of climate change mitigation.

World-wide estimates for the costs of CO_2 storage in depleted oil reservoirs, depleted gas reservoirs, and unmineable coal beds as a function of cumulative quantity of CO_2 stored have been developed in recent IEA Greenhouse Gas R & D Programme studies. The cost data quoted below include an allowance for the cost of transmission but not capture.

Depleted oil fields have an estimated total capacity of 126Gt of CO_2. As a result of the enhanced oil production some 120Gt could be stored at net cost saving. This calculation is based on a price of oil of US\$10/bbl; higher oil prices would improve the economics.

Depleted natural gas reservoirs have considerably larger CO_2 storage capacity of roughly 800 Gt. In the absence of significant enhanced gas production, there would be a small cost for injection. Some 105 Gt CO_2 can be stored at a net cost of less than US\$7/t CO_2 with a further 575 Gt at a cost of US\$10-17/t.

The total CO_2 storage capacity in unmineable coal beds is about 150 Gt. In the most favourable coal basins, an estimated 15 Gt of CO_2 may be sequestered and generating surplus of up to US\$20/t of stored CO_2 (not including the cost of capture), based on a natural gas price of US\$2/GJ.

Firm estimates for the CO_2 storage capacity in deep saline formations have not yet been developed. Rough estimates of the storage capacity, made in the early 1990s, lie between 400 and 10,000 Gt CO_2. More research is needed on the capacity of deep saline formations as well as the storage costs, which at the present time are considered likely to be between \$US5 and \$US17/t CO_2.

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

The IEA Greenhouse Gas R & D Programme has completed several studies evaluating the performance and costs of power generation options with and without CO_2 capture. Generation technologies considered include supercritical pulverised coal fuel (PF) station with post-combustion CO_2 capture using amine scrubbing, integrated gasification combined cycle (IGCC) with a shift reactor and pre-combustion CO_2 capture using physical solvent scrubbing, and a natural gas combined cycle (NGCC) plant with post-combustion capture using amine scrubbing. In each case the power plant generated a nominal 500 MWe and CO_2 was compressed to 110 bar for transportation.

1.6.1. Power Station Performance

Figures 4 and 5 compare power station efficiencies and CO_2 emissions for the cases studied. CO_2 capture in all cases exceeds 80% but reduces the plant efficiency by between 6.5 and 12.6 percentage points. An NGCC plant with CO_2 capture has both the highest generation efficiency and lowest CO_2 emissions rate. The reduction in efficiency from fitting capture is less for an NGCC plant than for a coal-fired plant primarily because less CO_2 must be captured and compressed per unit of electricity. Different coal-fired power cycles will exhibit both a range of efficiencies and a range of efficiency penalties for the addition of CO2 capture. These ranges are reflected in Figure 4.

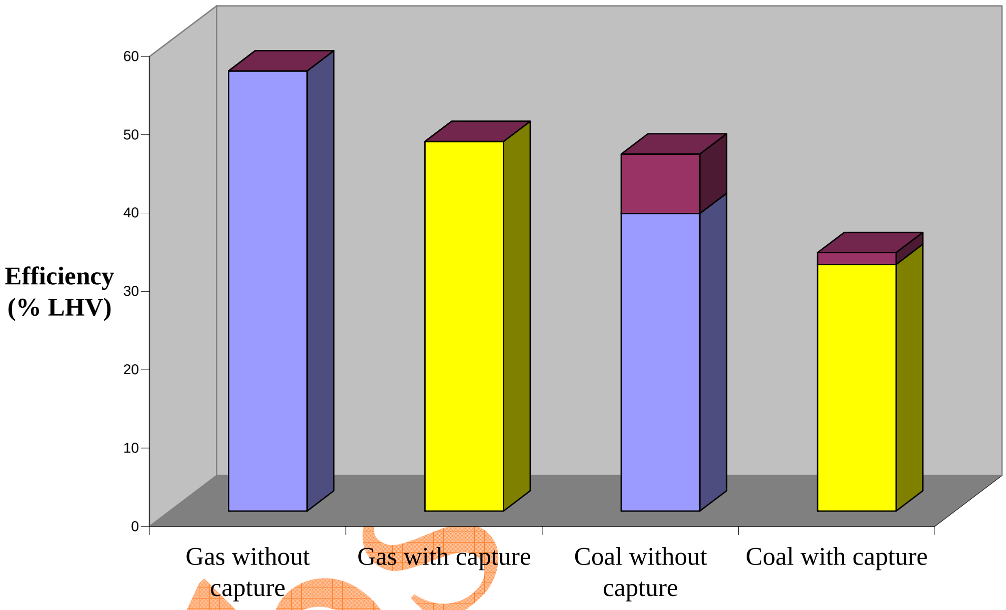


Figure 4. Power Station Generation Efficiencies (courtesy of the IEA Greenhouse Gas R&D Programme) for NGCC and a range of coal plant

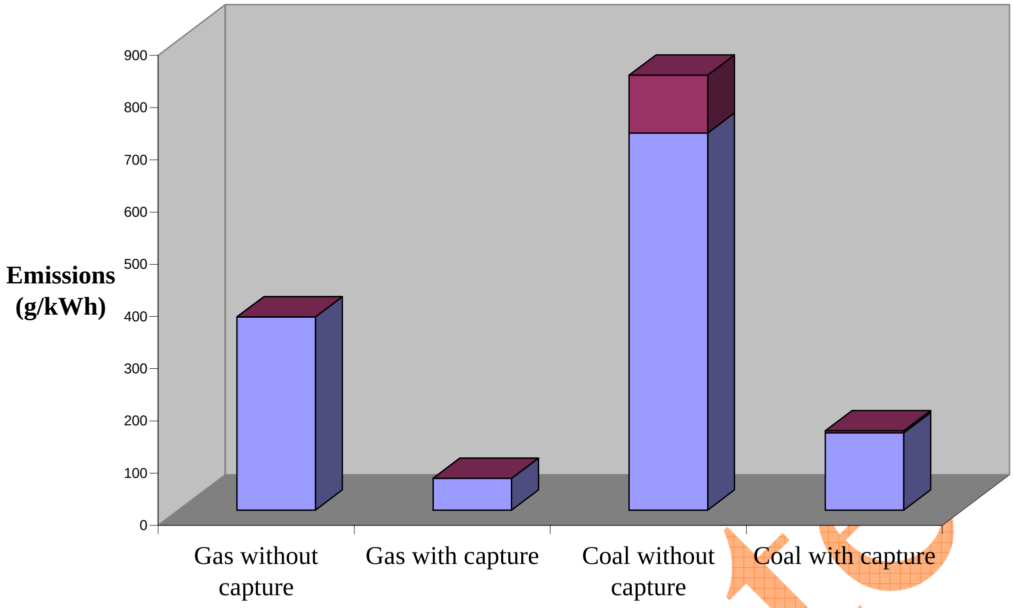


Figure 5. Power Station CO_2 Emissions (courtesy of the IEA Greenhouse Gas R&D Programme) for NGCC and a range of coal plant

1.6.2. Power Generation Costs

CO_2 capture and compression approximately doubles the capital cost of an NGCC plant, increases the cost of a PF plant by 80%, and that of an IGCC plant by 50%. These estimates are said to be accurate to within ±25%. The order of capital costs is the same with and without CO_2 capture - the NGCC plant is least expensive and the IGCC plant is most expensive.

The cost of electricity for the gas and coal-fired plants as a function of fuel cost is shown in Figure 6. An NGCC plant without CO_2 capture has the lowest cost of electricity; adding CO_2 capture increases the cost by about 1¢/kWh. Adding CO_2 capture to the coal plant, increase the cost of electricity by 1-2 ¢/kWh depending on the cost of fuel and type of plant. The costs were calculated assuming a 10% discount rate, base load operation and a CO_2 transport and storage cost of $8/t CO_2 stored.

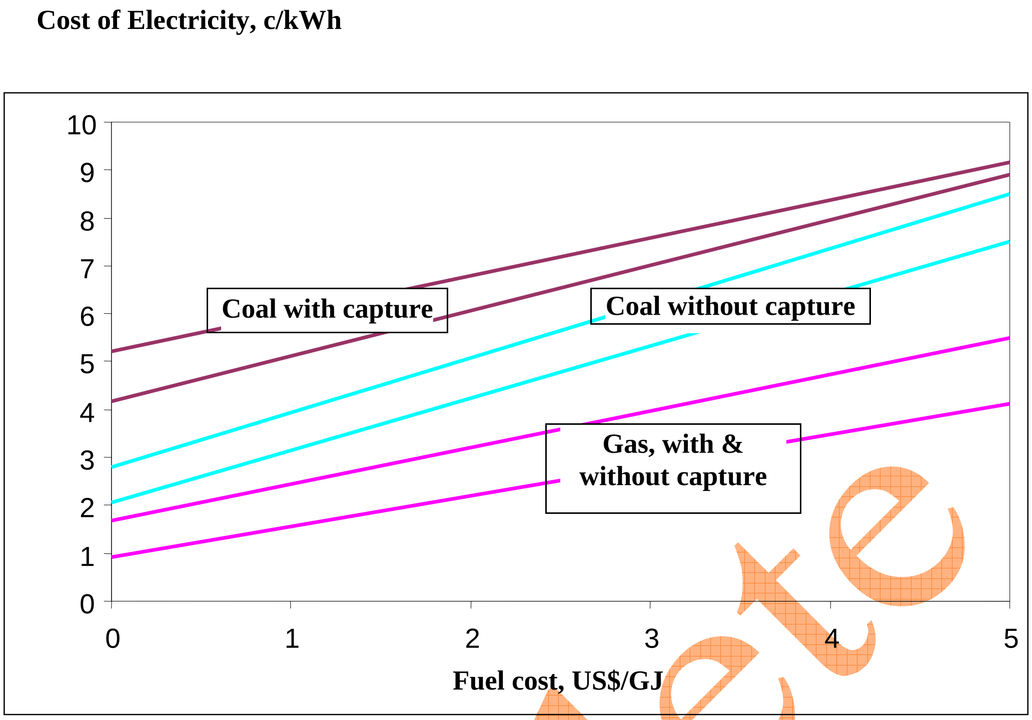


Figure 6. Costs of electricity generation with and without CO_2 capture and storage (courtesy of the IEA Greenhouse Gas R&D Programme)

1.7. Security of Storage

1.7.1. Natural Analogues of CO_2 Storage

Much can be learned by studying natural underground reservoirs of CO_2. Core sampling provides information on the geochemical reactions that occur between stored CO_2 and the underground formation. Slow leakage has been found at some natural sites, which provides a laboratory to study environmental and safety implications. The fact that CO_2 has been securely stored for perhaps millions of year will be important in gaining public acceptance of underground CO_2 storage.

1.7.2. Commercial Analogues of CO_2 Storage

Transportation and certain aspects of CO_2 storage are analogous in many respects to natural gas transportation and storage. While small in comparison, relatively large quantities of CO_2 are routinely transported by pipeline in association with enhanced oil recovery projects. Operating procedures and safety standards have been developed. There is increasing experience with underground injection of CO_2, which has also developed as an offshoot of natural gas injection and storage.

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-pressurization during injection as this could activate fractures and lead to leakage. The largest concern about CO_2 storage in oil and gas fields is the integrity of the many wells drilled during the production phase of the operation. Cement degradation, casing corrosion, or damage to the formation near the well could result in leakage.

1.7.3. Implications and Understanding of CO_2 Leaks

If underground leak paths are established the CO_2 could migrate upward and mix with fresh water aquifers or even reach the surface. Chemical interaction of CO_2 with the formation to produce carbonates causes swelling and is normally favourable for CO_2 storage.

CO_2 is less dangerous than natural gas so that safety concerns are correspondingly decreased. However, CO_2 is heavier than air (natural gas is lighter) and is an asphyxiant. There may be safety concerns in the immediate vicinity of a large-scale emission. Leaks from damaged oil and gas storage reservoirs could accumulate in secondary traps at higher elevations. Small-scale leaks that reach the surface should not create significant safety concerns as the CO_2 will disperse under normal climatic conditions. The rate of dispersion, however, will be slower than with lighter gases so that for a time there may be accumulation in low lying areas such as ditches, tunnels, or even basements.

Technology developed to control of natural gas blowouts can be used to control CO_2 wells. In spite of the moderate safety concerns associated with CO_2 leaks, all leaks that reach the surface will negate the overall objective of long-term CO_2 storage and are to be avoided.

1.7.4. Risk Assessment

Risks created by CO_2 capture at the power plant will be no more severe than already exist in association with the high temperature combustion and power generation process, which are well-known and readily managed.

Pipelines are currently used to transport CO_2 to the injection sites. Much larger quantities may be transported in the future. Procedures for CO_2 transport have largely been adapted from natural gas pipeline experience. Pipeline incidents will occur, probably with about the same frequency as natural gas pipeline incidents. However, from past experience, it may be expected that damage would be significantly lower in CO_2 pipeline incidents.

While oil and gas reservoirs are reasonably well characterized at present, less is known of the characteristics of unmineable coal beds and deep saline formations. Operating procedures for re-injection of natural gas and acid gas into appropriate storage sites have been developed, and should be broadly applicable to CO_2 injection. Most of the risks of storing CO_2 will be less than for natural gas storage although two factors – the increased density and the storage duration – may result in increased risks for CO_2 storage.

Risks associated with ocean storage will also need to be addressed.

Careful monitoring will be a key factor in anticipating incidents and minimizing their effects if they occur.

1.7.5. Environmental Impact Assessment

Environmental impact assessments are now required in many instances where new operations or significant changes in existing operations are planned. These documents provide a formal assessment of risks to the environment and describe methods to be used to manage the risks. An opportunity for public comment is usually provided before the project is given permission to proceed. Such a study, which forces the proposed operator to examine all of these features in a formal manner, can be of value to the project even when not required.

1.8. Other Aspects of CO_2 Capture and Storage

Because CO_2 capture and storage has been developed from known technology, it has been possible to establish, in a relatively short period of time, its technical feasibility as a mitigation option. The level of understanding of other, non-technical aspects, such as the attitude of society, the methods of financing, or the legal implications have not yet been developed to the same extent.

It will be essential to be able to demonstrate that CO_2 capture and storage is a cost-effective mitigation option in likely scenarios. This is being undertaken through systems modelling work, to compare this with other mitigation options and considers how they will be used together. Commercial players will need to understand the market for mitigation technologies and see CO_2 capture and storage in context with other options. The operators must have means of recovering the additional costs they will incur. The planning of major projects, such as pipelines, presents well known problems but the sheer scale of the investment needed may not be not fully appreciated yet.

Without wider understanding of the dangers of climate change, the public are unlikely to accept the additional costs involved in any mitigation measure, especially the more expensive ones required for making deep reductions in emissions such as CO_2 capture and storage. Some preliminary surveys have been carried out in various countries to find out what the public knows, whether society is willing to adopt precautionary measures against the more severe outcomes of climate change, or whether there would be acceptance of CO_2 capture and storage as a mitigation option. Factors which may have an important influence on public opinion include the security of CO_2 storage, the regulatory framework for using this technology and demonstration that it does not contravene the law.

MODULE 2: ONGOING ACTIVITIES IN CO_2 CAPTURE AND STORAGE

2.1. Introduction

This module summarizes ongoing activities on the capture and storage of CO_2. Current and planned activities in the capture and underground storage phases are summarized in Figures 7 and 8. Figure 7 shows the locations of plants in which CO_2 is separated from gas streams and subsequently injected underground and some future projects where CO_2 may be injected and stored. In most cases the CO_2 is separated from reducing gases and injected as part of enhanced oil recovery projects. These projects generally do not include the monitoring which will be needed for future wide-spread adoption of CO_2 control technology.

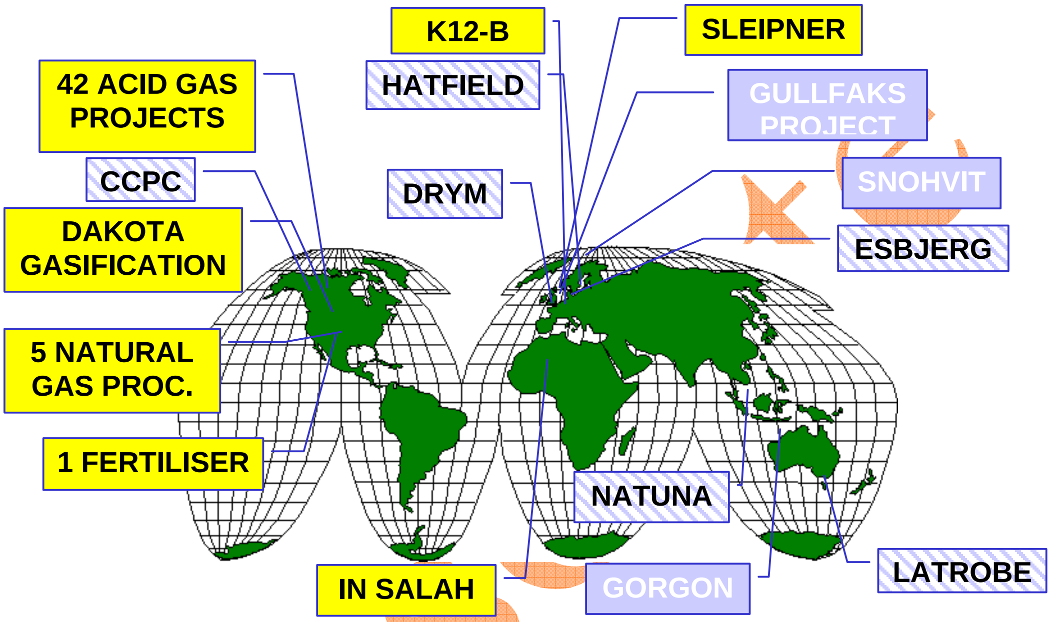


Figure 7. Current (dark lettering), proposed (light lettering) and possible (cross-hatched) projects involving CO_2 Capture for Injection.

Figure 8 presents an overview of underground storage projects, both current and planned, that include extensive monitoring. The Sleipner, Weyburn, RECOPOL and CRUST projects are currently active, the Frio, West Pearl Queen and RITE projects have conducted injections and are monitoring results, while the others are in various stages of planning.

The cumulative quantity of CO_2 stored (actual and projected) in six capture and storage projects is shown in Figure 9, starting with the Sleipner project in 1996 and projecting to the projects expected to come on stream by 2010. Earlier EOR and acid gas projects will have also resulted in some storage of CO_2 but, as these were not carried out specifically for the purpose of climate change mitigation, their contributions have not been included in this figure. By 2010 the total quantity of CO_2 stored should approach 60Mt.

Descriptions of CSLF member programme activities can be found on the CSLF web site www.cslforum.org.

Other major international programmes that are particularly relevant are those of the CO_2 Capture Project (www.co2captureproject.org/index.htm) and the IEA Greenhouse Gas R&D Programme (www.ieagreen.org.uk).

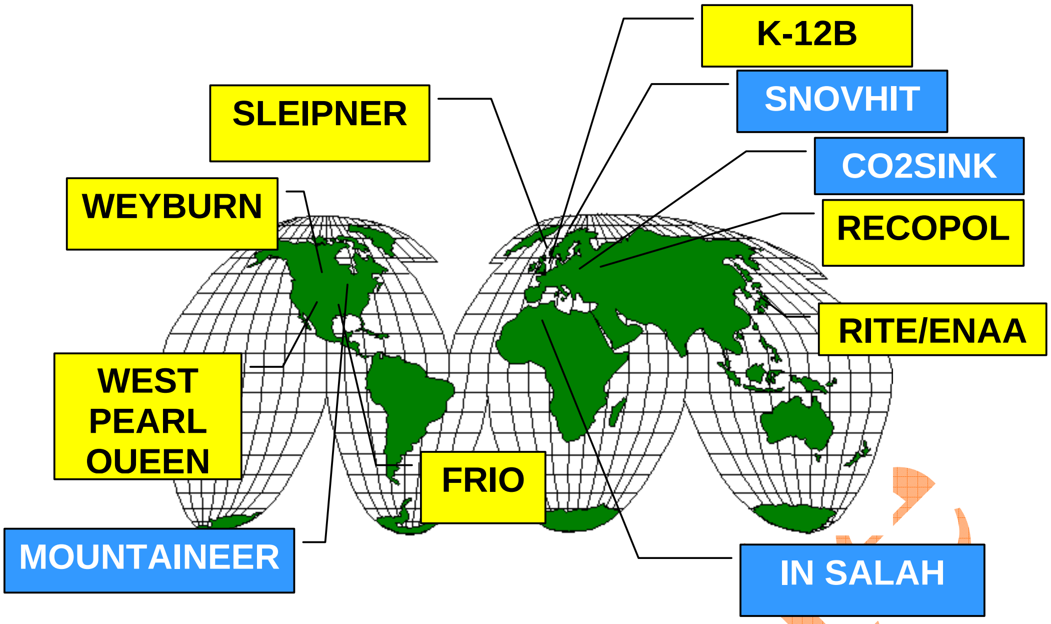


Figure 8. CO_2 Storage Projects where monitoring is currently being conducted (dark lettering) or may take place in future (light lettering).

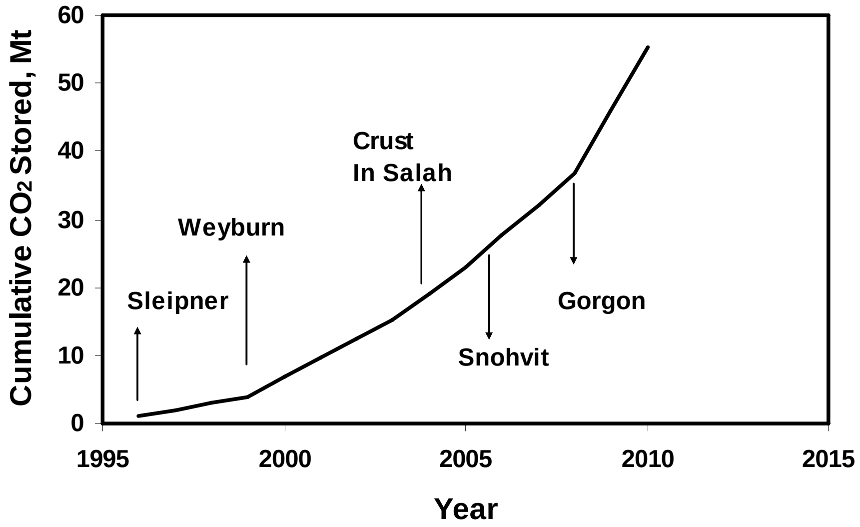


Figure 9. Cumulative amount of CO_2 captured and stored between 1995 and 2010 in the six projects indicated

2.2. Individual Projects Overview

Perhaps the most complete single source of individual research, development, and demonstration activities in the area of CO_2 capture and storage can be found on the web site www.co2sequestration.info maintained by the IEA Greenhouse Gas R&D Programme. This site contains descriptions of approximately 90 projects under the following classifications (some of the broad-based programmes fit within several of the classes).

- Commercial CO_2 Capture: Eleven installations are notable because they can be seen as demonstrations of capture technology in plants similar to what would have to be done to restrain greenhouse gas emissions. Five of the projects are located in the USA, four in Asia, one in Europe, and one in South America. Ten of the projects use a chemical absorption process while one uses physical absorption. Eight of the chemical absorption projects use MEA-based solvent, one uses MDEA, and one uses KS-1 solvent. In six cases the CO_2 is captured from the flue gas of power plants or industrial boilers – four coal-fired and two gas-fired. Capture occurs from the flue gas of an ammonia reformer in three cases, from natural gas purification in one case, and from coal gasification product in one. CO_2 is injected underground in two projects, used in the food industry in five cases, in the manufacture of urea fertilizer in three cases, and in a brine carbonation process in one project.
- CO_2 Capture R&D: Thirty-five projects of which six involve research in chemical absorption, four physical absorption, six oxyfuel combustion, eight membrane separations, one solid sorbents, and nine are classified as general. These projects are located in Asia, Australia, Europe and North America.
- CO_2 Geologic Storage Demonstration: Twenty-six projects, 12 of which involve experimental field work while 14 are limited to assessment and evaluation. Five of the experimental projects address aspects of EOR, five involve saline formations, two involve injection into hydrocarbon reservoirs, and two look at the special case of acid gas injection. Two of the assessment and evaluation projects are tied directly to experimental geologic storage projects. Others are addressing such questions as the long-term viability of large-scale geologic storage, monitoring requirements, and risk assessment. The aim of other projects is to establish a database of potential storage sites and to match CO_2 generation sites with potential stores.
- CO_2 Geologic Storage R&D: Seventy-four projects. Included are dual use/storage possibilities such as ECBM (16 listings), EOR (14 listings), and EGR (two listings). Sixteen projects are studying deep saline formations, with seven of these examining natural analogues and nine studying the storage of captured CO_2. There are seven projects addressing modelling and mapping, six studying monitoring and verification problems, six devoted to safety and the environment, and three are classified as "other". These projects are being conducted on a worldwide basis.
- CO_2 Deep Ocean Storage R&D: Nine projects. Studies are being conducted in Japan, the USA, and Europe to evaluate the feasibility of ocean storage. Two projects in the USA have constructed specialized research facilities for duplicating experimental conditions in the deep oceans. Small-scale laboratory experiments have been carried out in Japan and the USA. Other research is directed at describing and predicting the behaviour of CO_2 in the oceans and its impact on ocean biological systems.

In addition, there are many other research activities worldwide relevant to CO_2 capture and storage

The CSLF Technical Group recognizes that there are several international and national initiatives involved in CO_2 capture and storage activities and will endeavour to coordinate with these activities. The international initiatives include the IEA Greenhouse Gas Programme (IEA GHG), the Intergovernmental Panel on Climate Change (IPCC), and the International Partnership for the Hydrogen Economy (IPHE).

MODULE 3: GAP IDENTIFICATION

The ultimate objective of the 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. In this module this broad objective is broken down into a number of more specific targets in respect of the particular technologies. This is followed by discussion of the gaps between current capabilities and that which would be required to meet these goals. If these gaps can be filled, this should lead to achieving the ultimate objective of safe and cost-effective capture and storage technology.

3.1. The Need for New/Improved Technology

Much of the current implementation of CO_2 capture and storage is occurring in the natural gas industry where capture is required for commercial reasons and the incremental cost of storage is relatively small. Wider implementation in the power generation and other industries is needed, but is unlikely to occur until emission regulations or incentives to limit the discharge of CO_2 to the atmosphere are in place. Cost reductions are needed to reduce the financial burden of CO_2 capture and storage and so accelerate implementation.

Although currently expensive, CO_2 capture and storage is not necessarily more costly than other climate mitigation options such as solar or wind power. In order to understand its potential role, the cost-effectiveness of CO_2 capture and storage needs to be measured relative to the other mitigation options.

CO_2 capture is currently the most costly step in the overall capture, transmission and storage sequence. Significant power station efficiency penalties are associated with capture. Amine absorption, the current leading process for CO_2 capture has, for practical purposes, been “borrowed” from the natural gas, refining, and chemical process industries where it is used for the removal of acid gases such as CO_2 and H_2S from reducing atmospheres. While incremental reductions in costs for CO_2 capture in the oxidizing flue gas atmosphere are certainly possible, it is necessary to find out whether large cost savings are available with this relatively mature technology. If not, other plant configurations, other separation technologies or more radical approaches to the capture of CO_2 will be needed to accelerate implementation.

Relative to CO_2 capture, transmission costs are relatively low and the technology problems are reasonably well understood. It is assumed that the CO_2 would be dried and compressed to the liquid state at the point of capture. High pressure pipelines and/or ship tankers are the favoured modes of transportation. Transmission costs are, of course, distance dependent so the power station should be located in close proximity to a storage site wherever possible. There is limited need for new technology in this area, although tankers of the necessary capacity have yet to be built. In contrast, the sheer scope of creating a major CO_2 pipeline transmission system, some of which is likely to be located in populated areas, will raise legal, institutional and regulatory issues and there may be concerns from the public which must be addressed.

The largest capacities for CO_2 storage are in geologic formations (deep saline formations, depleted oil and gas reservoirs, and unmineable coal seams) and the deep oceans. The primary areas of concern are the 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 geologic sites is needed to provide baseline concentrations and information on levels of seepage. Risk assessment is being developed as a tool to inform decision makers about this aspect; international comparison of these methods will be an important part of verifying their predictions.

A clear understanding is required of any processes proposed for utilizing captured CO_2 to ensure that the changes in emissions from the whole system are taken into account in evaluating the proposed utilization process.

It is necessary to demonstrate CO_2 capture and storage in several large-scale projects in order to optimize the technology and reduce cost, to establish industrial capability for the manufacture and installation of the plants, to train operating personnel, and to develop best practice guidelines.

Other aspects of the process will influence technical decisions about this technology. For example, the nature of 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, should be amended to take climate change into account, as this is a problem not envisaged at the time the conventions were framed.

Technology developers must be able to secure adequate financing, for which they will need to be able to present a convincing case to bankers and other sources of funding, who will in turn need assurance from engineering professionals about the viability of the project. This emphasises the need for experience with the technology, in capture plant, in pipelines and in storage installations. Those implementing the technology will need to recover the added costs of CO_2 capture and storage, and improved methods of monitoring and verification of stored CO_2, as well as methods of detecting any leakage, will be required.

In view of the extremely long-duration required for CO_2 storage, the potential liability must be understood, so that long-term plans can be put in place. Public awareness of the need for action in the area of climate changes and the advantages of CO_2 capture and storage relative to other mitigation option must be increased; public attitudes are a key factor influencing politicians and regulators. This will require several more large scale monitored demonstrations of CO_2 storage.

Implementation of projects to answer these needs will not only result in improved technology but will also lead to improved cost estimates and (hopefully) cost reductions. CO_2 capture and storage provides a relatively rare opportunity for a new technology to effectively position itself ahead of the actual need.

Summary of key needs:

- Demonstrate CO_2 capture and storage in several large-scale plants;
- Determine how CO_2 capture and storage fits in the portfolio of mitigation options;
- Reduce CO_2 capture cost and efficiency penalties;
- Improve understanding of long-term security and environmental impact of storage;
- Improve monitoring both for safety and verification purposes;
- Develop accounting procedures for emission reductions.

3.2. Technology Gaps

3.2.1. CO_2 Capture Gaps

Significant reductions in post-combustion CO_2 capture costs may require the development of alternative solvents that, relative to amines, possess a combination of the following properties: less corrosive, less subject to degradation, have greater CO_2 capacity, require less energy for regeneration, and operate at higher temperatures. Other opportunities exist for cost reduction in oxyfuel and pre-combustion capture where there are variations possible in the capture conditions, and more flexibility for integrating CO_2 capture and power generation steps.

Alternative H_2 production processes that result in reduced cost and/or improved efficiency are important for the IGCC process with CO_2 capture. Lower cost O_2 would make IGCC more attractive. Membrane-assisted and sorption-enhanced production processes are being studied. Durability of the membranes and sorbents are the key factors. Alternative processes, such as oxyfuel combustion and chemical looping combustion, involve radical changes in power generation technology. Lower cost O_2 production and turbines capable of efficient operation in a high-CO_2 recycled gas stream are keys to the oxyfuel process. Development of oxygen-transfer solids having appropriate multi-cycle durability is the key need in the chemical looping process. Alternative post-combustion capture concepts based on solid sorbents rather than liquid solvents may be used. Multi-cycle sorbent durability is the key to the success of such concepts. The potential for all of these options to make more than incremental reduction in capture cost has to be demonstrated. Further evaluation of the potential of these concepts is needed before large-scale development begins.

3.2.2. CO_2 Transport Gaps

Pipeline accidents occur infrequently in the natural gas industry and must also be expected in CO_2 transmission pipelines. While the collateral damage associated with CO_2 pipeline accidents should be much smaller because of the absence of fire and explosion dangers, it will be necessary to develop appropriate response and remediation procedures.

Major expansion of the CO_2 pipeline network will be required before large scale capture and storage of CO_2 becomes a reality. Pipeline construction presents no major technology problems, but the expansion will, no doubt, raise significant non-technology issues.

Knowledge gaps exist concerning scale-up of tanker transport of liquid CO_2.

3.2.3. CO_2 Storage Gaps

While deep saline formations are believed to possess the largest CO_2 storage potential of the geologic options, there is uncertainty about their capacity and geological properties. In addition to uncertainty about the extent of the resource, gaps include site-specific knowledge such as the thickness and stability of the cap-rock, formation depth, long-term lateral transport of the saline water (and consequently the CO_2), and the rate and effect of geochemical interactions between CO_2 and the reservoir formation.

The extent of depleted oil and gas reservoirs, as well as their geology was relatively well defined during the oil and gas exploration and production stages. However, additional understanding of the geochemical reactions between CO_2 and the formation is needed. The security of the reservoirs, at least prior to the beginning of exploration and production, was implicitly guaranteed by the presence of oil and/or gas. Questions concerning the effects of exploration and production on the reservoirs exist. Drilling, acid treatment, and fracturing may have damaged the formation. Maximum damage would be expected in the vicinity of wells but there is always the possibility of damage even to the cap-rock. Perhaps the largest question concerns the integrity of abandoned wells. Corrosion of the well casing and improper cementing may ultimately lead to leaks. Over-pressurization of the reservoir must be avoided in case existing faults are opened up or new faults created. This could be a factor in deciding whether or not to use a particular reservoir.

The major questions concerning CO_2 storage in unminable coal seams are determined by the relatively low permeability of many coals, and the fact that coal is known to swell in the presence of CO_2, thereby reducing the permeability still further. Whether these are as limiting as predicted needs to be clarified and methods of improving the permeability of coals, such as fracturing as used in oil and gas production, need to be assessed, to see whether they increase the permeability near the well for sufficient time and extent and in a cost-effective manner.

Potential environmental effects coupled with questions concerning the permanency of storage and the movement of ocean currents are the major problems in ocean storage. There is little information on the effect of pH on the whole chain of ocean marine life.

3.2.4. Gaps in Uses of CO_2

Enhanced oil recovery, because of the economic benefit of the produced oil, provides the largest near-term use of CO_2. Current technology, however, is optimized for oil recovery rather than CO_2 storage. In some cases the injected CO_2 at the end of the EOR period is removed and re-used in a subsequent EOR project. In order for EOR to make a large-scale, long-term contribution to CO_2 storage, there must be incentives to leave the CO_2 in place after the end of the EOR project and to alter operating procedures to recognize the importance of both oil production and CO_2 storage. The concept of enhanced recovery of gas needs to be proven in practice and the circumstances delineated under which it would be beneficial.

Enhanced coal bed methane production provides the opportunity for economic return in conjunction with CO_2 storage. While it is known that CO_2 injection will displace methane and retain CO_2, greater understanding of the displacement mechanism is needed to optimize CO_2 storage and to understand the problem of swelling and decreased permeability in the presence of CO_2.

The opportunity for a large-scale, economical chemical process that uses CO_2 as a raw material and produces substantial net reduction in CO_2 release from the whole system, whilst not anticipated, would be welcomed if demonstrated. Simple tests of net emission benefit are available which should be used prior to any practical experiments.

3.2.5. Gaps in Understanding the Potential for CO_2 Capture and Storage

Estimates have been developed of the CO_2 storage potential in depleted oil reservoirs, gas reservoirs, and for enhanced coal bed methane projects as a function of storage cost. Deep saline formations are known to provide much larger potential storage capacity and to be widely dispersed throughout the world but the total volume of the resource and its ultimate CO_2 storage capacity is highly uncertain.

Simply defining the volume of deep saline reservoirs and their CO_2 capacity constitutes a major knowledge gap. Additional information is needed on the salinity of water as well as the chemical composition of the formation. CO_2 solubility decreases with increased salinity and the geochemical reactivity depends on the rock composition.

The potential CO_2 storage capacity of the oceans is very large so the important gap is not one of capacity but of how to harness that potential, in particular in view of the potential environmental effects and long-term storage effectiveness.

Mineral carbonation provides a CO_2 storage option where the CO_2 is stored in truly permanent fashion. Large quantities of olivine and serpentine rock are found in certain parts of the world, in sufficient quantity to provide significant CO_2 storage capacity. Knowledge gaps are associated with the process for converting captured CO_2 into a mineral. Increases are needed in the rate of reaction before the process has any chance of becoming competitive. The environmental impact of large-scale disposal of solid material also needs to be examined.

3.2.6. Gaps Relating to Security of Geologic Storage

The security of geologic storage must be evaluated on the basis of the presence of gaseous, liquid or supercritical CO_2, or aqueous solutions, all of which have a potential for migration and leakage, if slight.

Site characterization and monitoring prior to storage, during injection, and following injection are important. The condition of existing boreholes and their reliability in the presence of CO_2 must be surveyed. Best practice guidelines have started to appear from current demonstration projects and more are needed; these must be carefully examined to determine their general applicability. Some site specific variation in guidelines will likely be required. Remediation plans must be developed prior to the beginning of operations to deal with all anticipated problems.

Extensive tests to define the volume of the formation, the thickness and integrity of the cap-rock and to identify the presence and character of faults are needed prior to injection. Background information on CO_2 concentrations at ground level are needed as well as background information on seismic activity in the area. Three dimensional seismic and other tools developed by the oil and gas industry must be adapted as necessary to follow the CO_2 plume movement. Low cost monitoring techniques are needed for long-term verification of stored CO_2 and to satisfy national accounts. The frequency of monitoring and the duration of the monitoring period are both unknowns at present, so that protocols must be developed.

During injection the 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-pressurization. Methods of monitoring must be sufficiently sensitive to detect CO_2 concentrations only slightly above the background level, at leak rates of less than 0.1% per year. 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 has yet to be determined. Remote sensing techniques may be used. Detailed mathematical models that have been carefully verified will be important, especially during the post-injection period. Measuring leakage rates and movement of the CO_2 plume are 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 recognize 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.

Summary of Key Gaps

- Alternative absorption solvents or materials that, relative to amines, reduce capture costs and increase energy efficiency;
- Alternative power generation processes that have the potential to produce improved economics compared with absorption capture;
- Response and remediation procedures developed in advance of the possibility of CO_2 pipeline accidents;
- Best practice guidelines for storage site selection, operation and closure, including risk assessment.
- Better understanding of CO_2 storage capacity and geological and geochemical properties of deep saline formations;
- Site-specific evaluation of possible storage reservoirs to identify damage due to hydrocarbon extraction and status of sealed boreholes;
- Understanding CO_2-coal interactions, especially with respect to the mechanisms of methane displacement and permeability decreases;
- Development of response and remediation plans on a site-specific basis prior to injection;
- Site-specific information on CO_2 background concentration and seismic activity;
- Instruments capable of measuring CO_2 levels close to background and to distinguish between CO_2 from natural processes and that from storage;
- Knowledge of the environmental effects of CO_2 injection in the deep ocean;
- Capability of ensuring long-term site security post-injection including verified mathematical models of storage.

MODULE 4: ROADMAP

4.1. The Role of the CSLF

As discussed in Module 2 of this roadmap, there are many activities on-going around the world aimed at the research, development, and deployment of CO_2 capture, transport, and storage technologies. This module describes the role the CSLF can play in this worldwide effort. This role is clearly stated in Article 1 of the CSLF Charter:

- to facilitate the development of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage
- to make these technologies broadly available internationally
- to identify and address wider issues relating to carbon capture and storage

The CSLF is neither a funding agency nor research council. There are many excellent organizations on both the national and international level that perform these functions. It is neither the desire nor intent of the CSLF to encroach upon these activities. Rather, the CSLF intends to add value to on-going and future activity in the field of CO_2 capture, transport, and storage through facilitative and collaborative efforts to close implementation gaps.

In Module 3, technology needs were identified. This module is a roadmap to address those needs.

4.2. Key Topics, Timescales, Goals and Milestones

One goal of this roadmap is to set priorities for the CSLF by identifying key topics that need to be addressed. For each theme, goals and milestones are established for various timeframes. It is not the intent of this roadmap to suggest specific projects to achieve these goals and milestones. The process for recognizing specific CSLF Projects is described in Article 4 of the CSLF Terms of Reference and Procedures.

The key topics for CSLF projects are:

- ***Lower Costs.*** The costs for implementing CO_2 capture, transport, and storage technologies in the power industry are comparable with large-scale renewable or nuclear options to combat climate change, but they are still expensive compared to the status quo today. Significantly lowering these costs will make it easier to implement climate policies. The two primary pathways being followed to lower capture costs are improving existing commercial processes and developing new technologies like zero-emission power plants.
- ***Secure Reservoirs.*** To gain public acceptance, it must be shown that any environmental, health, or safety risks associated with CO_2 storage are manageable, and that means to address these risks are technically and economically feasible. In addition, leaky reservoirs will be inefficient in keeping CO_2 emissions out of the atmosphere. For both these reasons, methodologies to identify, develop, and maintain secure reservoirs need to be created and large-scale demonstrations need to be carried out.
- ***Measurement, Monitoring and Verification (MMV) Technologies.*** To assure the effectiveness of CCS projects, acceptable monitoring technologies and verification protocols must be available.

Table 1 details the critical milestones to be achieved for each theme divided into three timescales. Since the current CSLF charter expires in 2013, one timescale is defined as beyond 2013. For the duration of the current charter, two timescales will be considered, i.e., 2004-2008 and 2009-2013.

Table 1. CSLF Milestones by Topics and Timescales

Topic/Timescale	2004-2008	2009-2013	2014 +
Lower Costs	• Identify most promising pathways • Set ultimate cost goals	• Initiate pilot or demonstration projects for the 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

A brief description of these milestones follows:

- ***Lower Costs.*** As discussed in Module 1, there are many potential pathways being investigated to lower costs. Research over the next 5 years should help identify the most promising of these pathways to move forward into pilot and demonstration projects. Also, the CSLF should set specific costs targets. While costs reductions are expected in all three timeframes, meeting the ultimate costs goals will occur after 2014.

- ***Secure Reservoirs.*** Module 2 documented the many field experiments either underway or in planning today. The CSLF should promote and facilitate these activities over the next 5 years. Desired results from these activities include identification of the most promising reservoir types for CO_2 storage, development of reservoir selection criteria, and estimates of worldwide storage capacity. Several larger commercial scale CO_2 storage operations, should be underway by 2014.

- ***Monitoring and Verification Technologies.*** As described in Module 1, there are many technologies for monitoring and verification that exist today. However, they may need to be modified to meet the requirements of CO_2 storage. The specific monitoring and verification requirements are still evolving and will be driven, in part, by some of the non-technology needs being addressed by the CSLF Policy Group. As this information develops, specific monitoring and verification requirements can be identified and specific options can be assessed. These technologies can then be field tested, so as to be commercially available by 2014.

4.3. Types of Projects

As stated in the CSLF Terms of Reference, the CSLF will recognize collaborative projects in the following areas:

- Information exchange and networking
- Planning and road-mapping
- Facilitation of collaboration
- Research and development
- Demonstrations
- Other issues as indicated in Article 1 of the CSLF Charter

In addition, the CSLF has approved the following project recommendation guidelines:

1. The proposed project should be nominated by at least two CSLF Members.
2. The proposed project should be consistent with the CSLF Charter.
3. Project sponsors should be willing to share non-proprietary project information with other CSLF Members.
4. Visits to the project site should be allowed for representatives of CSLF Members.
5. The expected information from the project should be sufficient to allow others to make improved estimates of the technology's potential technical performance, costs, and benefits for any future applications.
6. The project should be started and major milestones reported prior to the expiration of the CSLF Charter (currently 2013).
7. Summaries should be made available, in English, for the CSLF website.

One purpose of these projects is to help close the existing technology gaps. Below, key technology gaps from Module 3 are listed by the technology theme:

1. ***Lower Costs***
    - Alternative absorption solvents or materials that, relative to amines, reduce capture costs and increase energy efficiency.
    - Alternative power generation processes that have the potential to produce improved economics compared with absorption capture.
2. ***Secure Reservoirs***
    - Response and remediation procedures developed in advance of the possibility of CO_2 pipeline accidents.
    - Best practice guidelines for storage site selection, operation and closure, including risk assessment.
    - Better understanding of CO_2 storage capacity and geological and geochemical properties of saline aquifers.
    - Site-specific evaluation of possible storage reservoirs to identify damage due to hydrocarbon extraction and status of sealed boreholes.
    - Understanding CO_2-coal interactions, especially with respect to the mechanisms of CH_4 displacement and permeability decreases.
    - Development of response and remediation plans on a site-specific basis prior to injection.
    - Site-specific information on CO_2 background concentration and seismic activity.
    - Knowledge of the environmental effects of CO_2 injection in the deep ocean.
3. ***Measurement, Monitoring and Verification Technologies***
    - Instruments capable of measuring CO_2 levels close to background and to distinguish between CO_2 from natural processes and that from storage.
    - Capability of ensuring long-term site security post-injection including verified mathematical models of storage.

Projects will be considered from all aspects of the CCS component chain, i.e. capture, transport, storage, and monitoring/verification. Table 2 summarizes where on the development status each of these components are.

Table 2. Development Status of CCS Components

CCS Component Chain	**Development Status**
Capture	***Commercial*** processes exist, but may be too expensive for this application New or improved processes that meet cost requirements are only at an ***R&D*** stage.
Transport	***Commercial***
Storage	***Commercial*** analogues (e.g., EOR) exist at reduced scale and/or timeframe. For anticipated scale and timeframes, technology is at ***development and/or demonstration*** stage.
Measurement, Monitoring, and Verification	Many ***commercial*** monitoring techniques exist, but ***development and demonstration*** are required to apply to CCS activities.

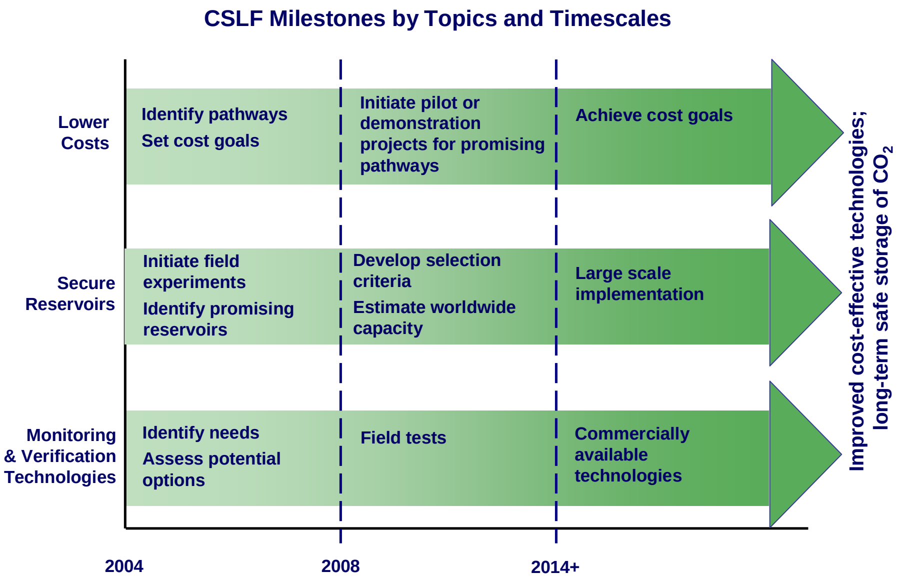
The different members of the CSLF have different capabilities to develop CO_2 capture, transport, and storage technologies. Through collaboration on projects, the CSLF utilize these complementary capabilities to address the technical challenges that lie ahead.

4.3. Summary

This roadmap has identified key milestones for the development of improved cost-effective technologies for the separation and capture of CO_2. for its transport and long-term safe storage. These milestones are summarized in Figure 10.

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.

Figure 10



This roadmap does not identify individual collaborative projects. Selection of specific projects must be done in accordance with the CSLF terms of reference and the project recommendation guidelines adopted by the CSLF. However, to provide some guidance, the roadmap does highlight the technology gaps for each theme, as well as the interests and capabilities of each of the CSLF members.

Finally, this roadmap is meant to be a living document. As new information is produced through the large number of research, development, and demonstration projects worldwide, those findings should be incorporated into this roadmap.