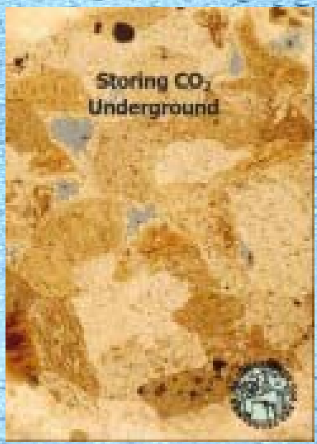
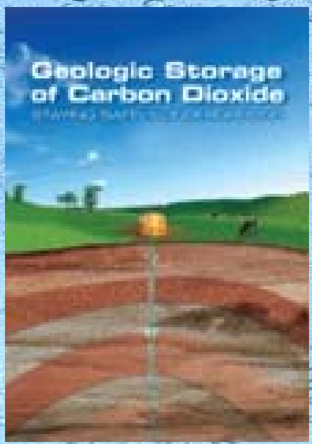
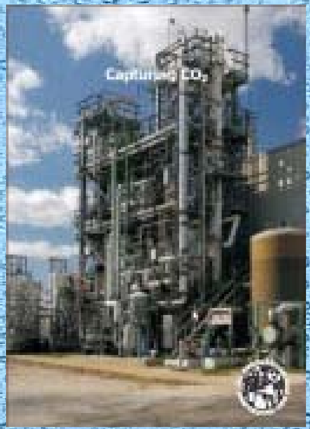
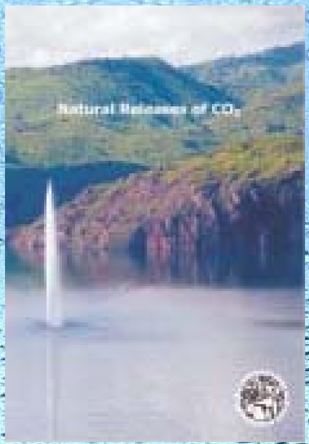
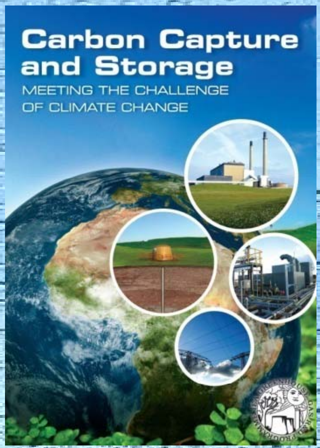
IEA GHG 2008 Brochures











Welcome

Brochure Summaries

IEA GREENHOUSE GAS R&D PROGRAMME

Welcome

The IEA Greenhouse Gas R&D Programme (IEA GHG) was established in 1991. Our role is to evaluate technology options for greenhouse gas mitigation, disseminate the results to key stakeholders and assist the implementation of the technology.

The focus of much of IEA GHG's work in recent years has been on CO_2 capture and storage (CCS). CCS is one of a portfolio of technologies that will need to be deployed to reduce significantly atmospheric levels of CO_2. CCS offers the potential to significantly reduce CO_2 emissions in the near term using the existing fossil fuel based energy infrastructure.

IEA GHG has prepared a number of summary reports on CCS that aim to provide more general information on the topic for both stakeholders and the lay public. This CD contains several of these summary reports for general dissemination at conferences and workshops. The reports provided include summaries on the status of CO_2 capture technology and on the status and readiness of geological storage. In these reports you can find information on the technology options, their current technical status and likely costs as well as attempts to answer key questions regarding the safety and environmental impact of CCS based on current research. One report compares the situation of geological storage with that of the famous Lake Nyos incident and finds that there are no similarities between engineered storage and this natural release as many of those against the deployment of CCS had inferred. The final report covers the suitability of CCS as a climate mitigation option and aims to address concerns over the readiness of CCS technology for deployment in both the near and long term.

For further information on IEA GHG and the summary reports we produce please look at our web site www.ieagreen.org.uk. We also host a web site that provides more detailed information on CCS : www.co2captureandsatorage.info .

Continue

Brochures

Capturing CO_2 - This report provides a summary of CO_2 capture processes. It also evaluates the effect of CO_2 capture on different power plant technologies, examining plant performances, investment and production costs as well as environmental impacts.
The report also discusses how the choice of power plant technology and CO_2 capture method can depend on many factors besides cost and efficiency as well as other influences.

Storing CO_2 Underground - This report provides a summary of how to capture and store CO_2 in geological formations. It highlights the benefits of CO_2 capture and storage, as well as how CO_2 can be captured and stored.
The report discusses how CO_2 can be trapped underground and identifies the best regions for suitable storage sites. It also provides a concept for what a future CO_2 storage operation might look like.

IEA GREENHOUSE GAS R&D PROGRAMME

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Natural Releases – This report looks at the circumstances that lead to natural releases of CO_2 and provides a factual and balanced overview on their relevance to geological storage of CO_2.

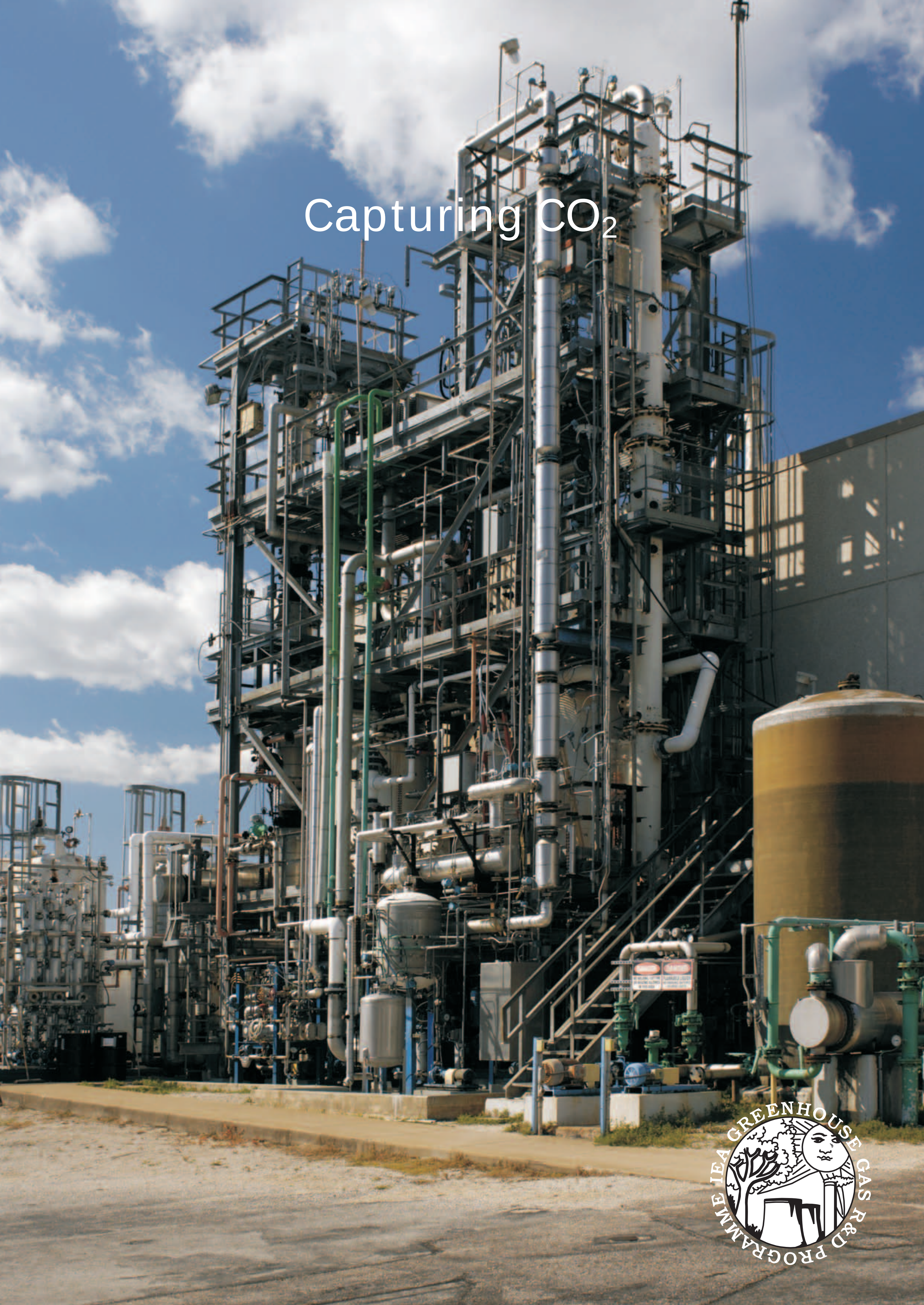
Geological Storage of Carbon Dioxide - This report looks at the factors governing the best assurance of safe and secure geologic storage. This includes a project that is well designed and conducted properly and carefully. More detailed explanations, including questions to ask about proposed projects to ensure that they are being conducted properly are available in this booklet.

Continue

Brochures

Carbon Capture and Storage- Meeting the Challenge of Climate Change – This report looks at CCS as a whole including what it is, why we need it, the cost and how ready we are to implement the technology.

Capturing CO_2



IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

Disclaimer

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Report compiled by Deborah Adams and John Davison

Cover Pictures : CO_2 pilot plant facilities at the University of Texas at Austin. The CO_2 is captured from the flue gas by alkanolamine absorption/ stripping. The facility aims to develop an evolutionary improvement to monoethanolamine (MEA) absorption/stripping for CO_2 capture from coal-fired flue gas.

By Christopher Lewis, © Separations Research Program 2007

CONTENTS

INTRODUCTION

Emissions of greenhouse gases are expected to cause climate change. The main greenhouse gas is carbon dioxide (CO_2) and the major source of it is the combustion of fossil fuels to supply energy. Emissions can be reduced by a variety of measures, such as improving energy efficiency and developing alternative energy sources, like wind and solar power. However, a rapid move away from fossil fuels is unlikely as energy supply infrastructure has a long lifetime, and such a move could destabilise economies.

Another way to reduce emissions is to capture the CO_2 that is released from fossil fuel-fired power plants and store it underground. This is the focus of this report, as power generation accounts for about one-third of CO_2 emissions from fossil fuel use. The current leading technologies for power generation are pulverised fuel (PF) combustion steam cycles and natural gas combined cycles (NGCC). The IEA Greenhouse Gas R&D Programme (IEA GHG) has assessed the performance and costs of these power plants, both with and without the capture of CO_2. Integrated Gasification Combined Cycle (IGCC) for the gasification of coal, which was included in the assessment, may be a suitable technology from which to capture CO_2. A number of criteria were specified for all the studies to enable the results to be compared in a meaningful manner. The main specifications are listed in the Annex at the end of the report.

CO_2 can be captured by a variety of methods which are classified as post-combustion, pre-combustion and oxy-combustion. Post-combustion capture uses a solvent to capture CO_2 from the flue gas of power plants. In pre-combustion capture the fuel is reacted with air or oxygen and then with steam to produce a mixture of CO_2 and H_2. The CO_2 is removed and the hydrogen is used as the fuel. Oxy-combustion is when oxygen is used for combustion instead of air, which results in a flue gas that consists mainly of CO_2 and is potentially suitable for storage.

The next chapter describes the capture processes in more detail. The effect on the power plants of capturing the CO_2 is explained later in this report, in terms of the reduction in efficiency, the emissions of CO_2 and the extra consumption of resources by the plant. The choice of power plant and CO_2 capture method is put in context by considering some of the other factors involved, such as the choice of fuel, as well as sensitivity to the cost of fuel and the load factor. The conclusions are drawn in the final chapter.

THE POWER PLANTS AND CAPTURE PROCESSES

The three different types of capture process for CO_2 are described in this chapter.

POST-COMBUSTION CAPTURE POWER PLANTS

Post-combustion capture normally uses a solvent to capture CO_2 from the flue gas of power plants. The solvent is then regenerated. The solvents for CO_2 capture can be physical, chemical or intermediate but chemical solvents, known as amines, are most likely to be used for post-combustion capture. This is because chemical solvents are less dependent on partial pressure than physical solvents are, and the partial pressure of CO_2 in the flue gas is low, typically 4-14% by volume. However, chemical solvents require more energy (as steam) to regenerate, that is, to break the relatively strong chemical link between CO_2 and the solvent. Sterically hindered amines need less steam for regeneration.

It is likely that amines will be used for the first generation of CO_2 post-combustion capture, because of the advanced state of development of amine absorption. However, the presence of oxygen can be a problem for flue gas amine scrubbing, as it can cause degradation of some solvents and corrosion of equipment. Inhibitors can be included in the solvent to counteract the activity of oxygen. At present the process of scrubbing CO_2 with amines does not operate on the scale of power plants, but increasing the technology to this size is not considered to be a major problem.

The flue gas must contain very low levels of oxides of nitrogen and sulphur (NO_2 and SO_x) before it is scrubbed of CO_2. This is because NO_2 and SO_x react with the amine to form stable, non-regenerable salts, and so cause a steady loss of the amine. The preferred SO_x specification is usually set at between 1 and 10 ppm(v). This means that post-combustion CO_2 capture on coal fired power plants requires upstream de-NO_x and flue gas desulphurisation (FGD) facilities. The limits for NO_x can usually be met by the use of low NO_x burners with selective catalytic reduction (SCR), and the SO_x limit can be achieved by some FGD technologies.

IEA GHG has assessed two proprietory processes for the post-combustion capture of CO_2, one based on MEA and the other based on a hindered amine solvent. The hindered amine process loses less energy mainly because the solvent consumes less heat for regeneration than MEA solvents. The data presented in this report are for the hindered amine process.

Post-combustion CO_2 capture processes can be considered a current technology, although some demonstration of these technologies at large coal-fired power plants is necessary.

PRE-COMBUSTION CAPTURE POWER PLANTS

Pre-combustion capture can be used for gas turbine combined cycles. In this process, a fuel is reacted with air or oxygen to produce a fuel that contains CO and H_2. This is then reacted with steam in a shift reactor to produce a mixture of CO_2 and H_2. The CO_2 is separated and the H_2 is used as the fuel in a gas turbine combined cycle, which is the most efficient thermal cycle for power generation, currently. Pre-combustion capture can be used in natural gas or coal based plants. When the primary fuel is coal, and the key process is the gasification of the coal, it is known as an integrated gasification combined cycle (IGCC). Gasification is the partial oxidation of coal, or any fossil fuel to a gas, often known as syngas, which has H_2 and CO as its main components. Gasification can act as a bridge between coal and gas turbines, with the target of high energy efficiency and minimum emissions to the environment. However, at present, none of the existing coal-fired IGCC plants includes shift conversion with CO_2 capture.

IEA GHG has assessed plants based on two types of gasifier:

- A slurry feed gasifier, in which the gas product is cooled by quenching with water; and
- A dry feed gasifier, in which the gas product is cooled in a heat recovery boiler.

In the slurry feed IGCC plant without CO_2 capture, the coal is ground and slurried with water and then pumped to the gasifier vessels where it reacts with oxygen. The products from gasification are quenched with water, the saturated gas is cooled, and condensed water and minor impurities are removed. The sulphur compounds are removed from the gas by passing it through a reactor and feeding it to a Selexol acid gas removal (AGR) plant. Selexol is a physical solvent. The clean fuel gas is fed to the gas turbine combined cycle plant.

However, in the case of the IGCC with CO_2 capture, the gas from the gasifier is fed to a CO_2-shift converter prior to cooling and the Selexol unit removes CO_2 as well as sulphur compounds. The Selexol is regenerated to produce separate CO_2 and sulphur compound streams. The CO_2 stream is compressed and dried for transport by pipeline. The removal rate of CO_2 is over 90%, which means that an overall CO_2 capture rate of 85% can be achieved.

In the dry feed gasifier plant without capture of CO_2, the coal is dried, ground and then fed to the gasifier vessels. The gasifier product gas is quenched, cooled and is then fed to a dry particulate removal unit. Some of the gas is recycled as quench gas and the remainder is scrubbed with water, reheated, the COS is removed and it is fed to an MDEA solvent acid removal plant. The clean fuel gas is fed to the gas turbine combined cycle plant. The configuration of the plant with CO_2 capture is the same except that the COS removal process is replaced by a two-stage shift converter and H_2S and CO_2 are separated in a Selexol AGR unit.

OXY-COMBUSTION CAPTURE POWER PLANTS

Oxy-combustion is the term for when a fossil fuel is combusted with nearly pure oxygen and recycled flue gas or CO_2 and water/steam to produce a flue gas consisting essentially of CO_2 and water. It may have potential as part of a system for capturing and storing CO_2 as the nitrogen concentration in the flue gas is much lower than when air is used for firing. So the CO_2 can be stored with less downstream processing.

The PF oxy-combustion plant uses the same steam conditions as the other post-combustion capture plant. A large amount of oxygen is required for combustion, which is obtained from an air separation unit.The flue gas from oxy-combustion is compressed and chilled to separate out nitrogen, oxygen and other impurities. The resulting CO_2 concentration is typically 95mol% or more.

The EU NO_x emission limits can be met with just the firing system of the boiler with staged combustion and low temperature at the furnace exit. The NO_x and SO_x will be converted to acid and condensed from the CO_2 stream, so SCR and FGD units may not be needed.

Oxy-combustion is at a relatively early stage of development but integrated pilot plants are being built and plans to build commercial power plants are also at an advanced stage.

PERFORMANCE OF THE POWER PLANTS

The principle aim of this comparison is to evaluate the effect of CO_2 capture on different power plant technologies. To this end, the plant performances, investment and production costs and environmental impact were examined.

POWER PLANT EFFICIENCY

The thermal efficiencies of the power plants with and without CO_2 capture are compared in Table 1, based on information from studies carried out by IEA GHG. The natural gas fired plants have the highest thermal efficiency (about 55-56%) of the plants without capture of CO_2. The efficiency is calculated on a lower heating value (LHV) basis. The PF and the dry feed IGCC have a similar net efficiency (43.1-44.0%). The slurry feed IGCC plant has the lowest efficiency at 38%. This is largely because there is a lower efficiency of conversion of coal to fuel gas in the slurry feed gasifier.

Table 1 Power Plant Thermal Efficiencies

Fuel	Power Generation Technology	CO_2 Capture Technology	Net Efficiency[a] % (LHV)
Coal	Pulverised fuel	None	44.0
		Post-combustion	35.3
		Oxy-combustion	35.4
	IGCC, dry feed	None	43.1
		Pre-combustion	34.5
	IGCC, slurry feed	None	38.0
		Pre-combustion	31.5
Gas	Gas turbine combined cycle	None	55.6
		Post-combustion	49.6
		Oxy-combustion	44.7

a. HHV efficiencies of the coal-fired plants are 0.956 times the LHV efficiencies. HHV efficiencies of the gas-fired plants are 0.904 times the LHV efficiencies

Capturing CO_2 requires energy and thus reduces the thermal efficiency of the plants. The NGCC plants still have the highest efficiency at 44.71-49.6% and the efficiency reduction for the capture of CO_2 is only 6.0-10.9 percentage points. The efficiencies of the dry feed IGCC, oxy-combustion and post-combustion coal-fired plants are similar, at 34.5-35.4%. The efficiency reductions for CO_2 capture on the same plant are 8.6-8.7 percentage points. Although the slurry feed IGCC plant with capture has the lowest efficiency at 31.5%, it also has the lowest efficiency reduction compared to the same type of coal fired plant without capture, at 6.5 percentage points.

There are a number of factors which contribute to the efficiency reductions for CO_2 capture, and they vary depending on the fuel and technology used for combustion. The factors and the effect they have on plant efficiency are summarised in Figure 1. It shows that the major source of energy reduction for post-combustion capture is the use of low pressure steam to regenerate the solvent used to capture CO_2. The natural gas fired plants with post-combustion capture of CO_2 have a smaller reduction in efficiency. This is because there is less CO_2 to be captured as natural gas has a lower carbon content per unit of energy than coal.

Figure 1 also shows that the IGCC plants with CO_2 capture lose less energy than the PF plants with CO_2 capture. This is because the CO_2 partial pressure is higher in the IGCC plants and so a less energy intensive physical solvent scrubbing process can be used. In the post-combustion capture plants the feed gas is close to atmospheric pressure and the concentration of CO_2 is lower, so a more energy intensive chemical solvent is required. In addition, the IGCC plants require less energy for CO_2 compression as some of the CO_2 is recovered at raised pressure.

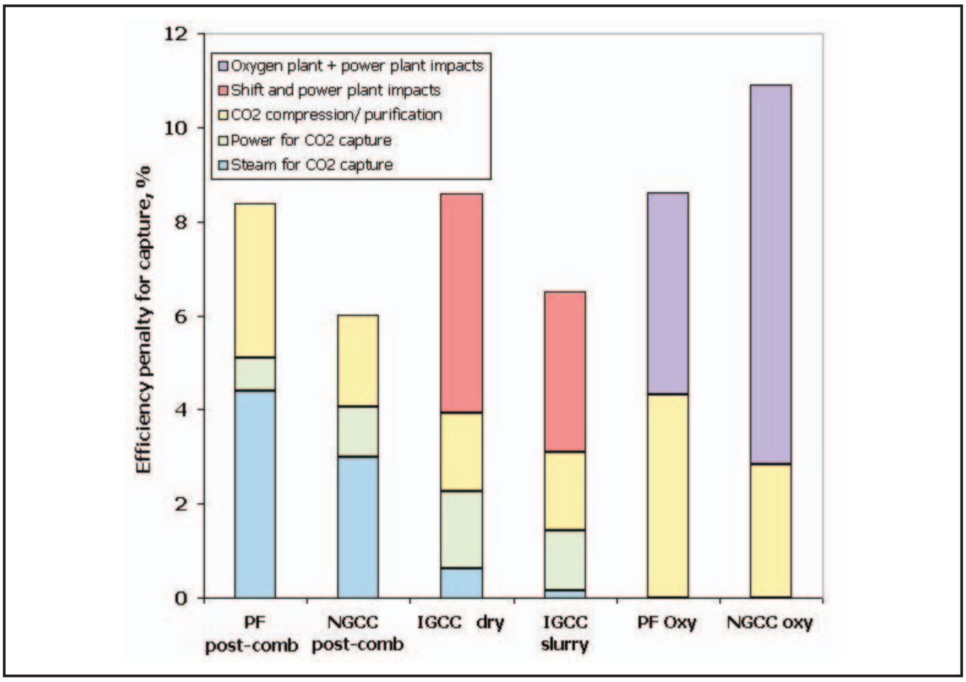

Figure 1 Breakdown of efficiency penalty for CO_2 capture

However, the IGCC plants have some of their own sources of energy loss. For example, the fuel gas is passed through shift reactors prior to the removal of CO_2, and the shift reactions are exothermic. Although most of the exothermic heat is recovered in steam generators, it means that energy bypasses the gas turbine and is fed directly into the steam cycle, which has a lower efficiency. The dry feed IGCC plant has a higher overall energy loss than the slurry feed plant because the raw fuel gas has a higher concentration of CO and so more shift conversion is needed. In addition, there is a requirement to add steam to the shift converter feed. Shift conversion and CO_2 separation also has an impact on the performance of the gas turbine combined cycle. Over half of the efficiency reduction caused by CO_2 capture in IGCC plants is the result of energy losses due to shift conversion and changes in the performance of the gas turbine combined cycle.

The oxy-combustion plant loses efficiency because of the electricity used by the oxygen production unit. This is slightly offset by smaller losses in the main power generation units such as not requiring an FGD plant. A higher volume of gas is fed to the CO_2 compressors due to the presence of impurities. Additional compression is necessary to drive the separation unit, which removes these impurities. The oxy-combustion NGCC plant uses less energy than the coal-fired one, but the reduction in efficiency is much greater. The amount of oxygen required per MW of fuel is about 15% lower for the NGCC plant, but the oxygen is produced at high pressure for feeding to the gas turbine. The result is higher overall energy consumption.

EMISSIONS OF CO_2

The amount of CO_2 emitted, captured or avoided by the power plants is shown in Table 2. The quantity of CO_2 avoided is the emissions per kWh of a plant with CO_2 capture, compared to the emissions of a baseline plant that does not capture CO_2. The baseline plant is that which would be displaced by a plant with CO_2 capture, so it may or may not be the same technology as that which displaces it. Three types of baseline plant are given in Table 2: the same type of power generation technology as that with CO_2 capture; a PF plant; and an NGCC plant.

Table 2 CO_2 emissions data

Fuel	Power generation technology	CO_2 capture technology	CO_2 emissions g/kWh	CO_2 captured g/kWh	CO_2 avoided g/kWh		
					Same techn-ology baseline	PF base line	NG CC base line
Coal	PF	None	743	—	—	—	—
		Post-comb	92	832	651	651	287
		Oxy	84	831	659	659	295
	IGCC	None	763	—	—	—	—
	(dry)	Pre-comb	142	809	621	601	237
	IGCC	None	833	—	—	—	—
	(slurry)	Pre-comb	152	851	681	591	227
Gas	NGCC	None	379	—	—	—	—
		Post-comb	63	362	316	680	316
		Oxy	12	403	367	731	367

The addition of CO_2 capture technology reduces the thermal efficiency of the power plant, which increases the production of CO_2. For this reason, when plants of the same power generation technology are compared, the amount of emissions avoided are lower than the amounts captured. However, in some circumstances plants with CO_2 capture may displace old, inefficient plants which would increase the amount of CO_2 avoided, beyond that shown in Table 2.

The post-combustion and pre-combustion CO_2 capture plants collect 85-90% of the CO_2, and the oxy-combustion plants 90-97%, as shown in Table 2. These results are not necessarily the technical limits or economic optima. More work is required to find the effects of percentage CO_2 capture on costs and efficiency for all the technologies.

Each technology produces a CO_2 of a different purity. If a high purity CO_2 is required, this may influence the decision as to which technology is selected.

CONSUMPTION OF RESOURCES AND OTHER EMISSIONS

CO_2 capture affects the consumption of raw materials, the quantities of waste and the emissions to the atmosphere per unit of electricity output. The reduction in thermal efficiency increases the consumption of raw materials. In addition, there is a need for some make-up solvent for post and pre combustion capture.

Post-combustion CO_2 capture plants use more solvent and produce more solvent residue than IGCC plants. Hindered amine is a more advanced solvent than MEA, thus less is required and less waste is produced.

Emissions of sulphur oxides to the atmosphere are expected to reduce, but emissions of NOx are expected to increase, exept for oxy-combustion.

From an environmental perspective, the optimum technology for coal-fired power generation will depend on the relative importance given to the consumption of different resources and the environmental impacts of different types of wastes and emissions.

CAPITAL COSTS AND COST OF ELECTRICITY GENERATION

The capital costs and costs of electricity generation for each technology are shown in Figures 2 and 3, but they are subject to a number of uncertainties including the fact that the capture technologies being considered have not yet operated in full scale commercial plants. Fluctuations in currency exchange rates and the market for plant, materials and fuel add more uncertainty.

However, Figures 2 and 3 do show that the capital costs and costs of electricity generation for the PF post-combustion capture, oxyfuel and dry feed IGCC plants are similar. The slurry feed IGCC plant has capital costs that are about 20% lower and the cost of electricity generation is 10% lower. However, all the studies are based on assumptions about plant performance and availability, and have yet to be demonstrated. In addition, costs can vary for different coals and plant locations. All the technologies considered have scope for improvement, so the relative costs could change in the future.

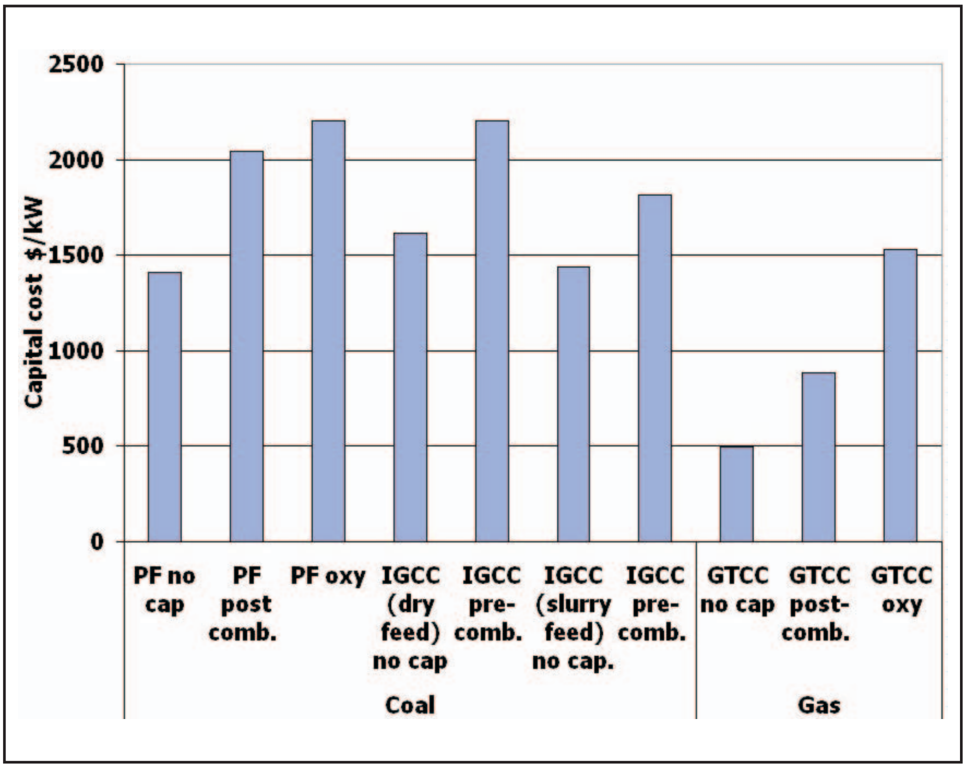

Figure 2 Power outputs and capital costs

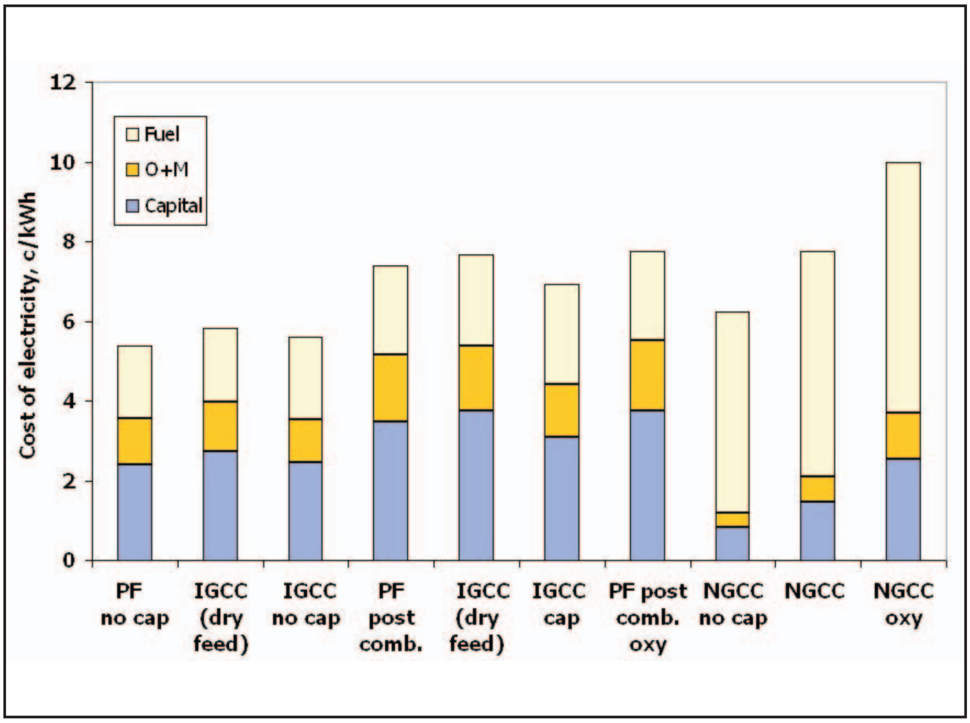

Figure 3 Cost of electricity

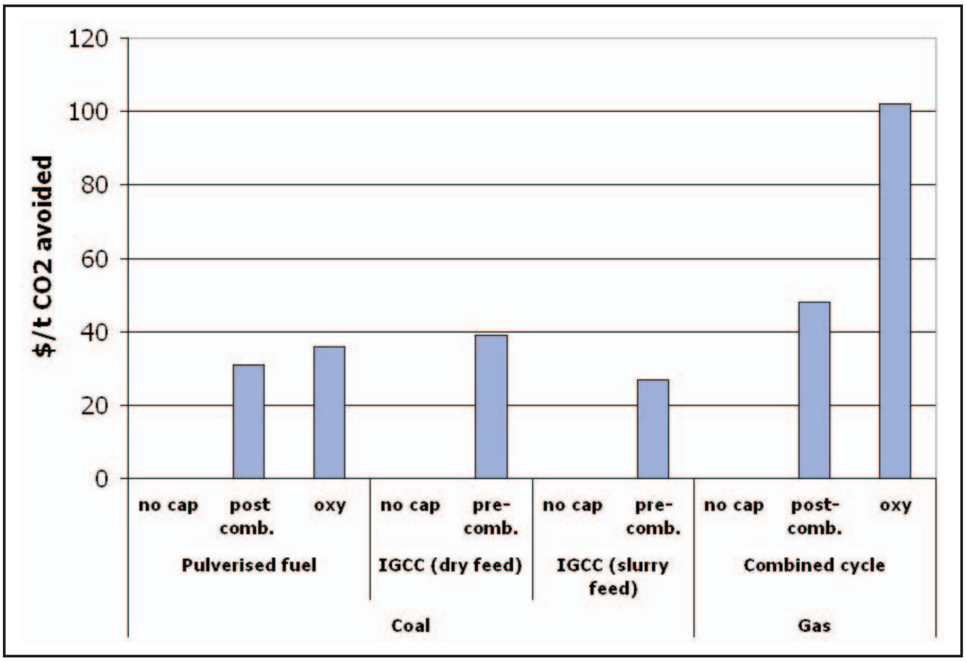

Figure 4   Cost of CO_2 avoided

SENSITIVITY TO COST OF FUEL

The cost of a major input, that is the fuel, feed into the cost of power generation. The price of fuel varies with location and time. For example, in a region where fuel is cheap to produce and the access to international markets is not easy, the price may be lower than internationally traded prices. Figures 3 and 4 are based on a coal price of $2.2/GJ and a gas price of $7.8/GJ (LHV basis). The effects of different fuel prices can be easily seen by scaling the fuel cost bar in Figure 3. The costs in Figures 3 and 4 do include the costs of CO_2 compression to a pressure of 11MPa but exclude transport and storage.

SENSITIVITY TO THE LOAD FACTOR

Figures 3 and 4 use cost data for base load plants, operating at a load factor of 85%. In the short term, power plants with CO_2 capture and storage are likely to operate at base load. This will maximise the use made of CO_2 capture and repay the investment more swiftly. However, in the longer term this may change. The need to reduce emissions of CO_2 may lead to a large increase in the use of renewables, such as wind and solar energy, which have low marginal operating costs and so will generally operate whenever they can in preference to other types of generating plant. As a result, other plants on the grid will have to operate at lower annual load factors to meet peak demands. The ability of power plants with a CO_2 capture facility to operate in this way will need to be assessed.

Table 3 shows a simple projection of the effects of load factor on the costs of electricity produced by NGCC and pulverised coal plants with post combustion CO_2 capture. At lower load factors the cost of electricity increases less for NGCC than for coal fired power plants. This is because the fixed costs of NGCCs are lower than those of coal-fired power plants. Plants with CO_2 capture are expected to work better in power grids containing substantial proportions of renewable energy than technologies that are more capital intensive and less flexible, such as nuclear power.

Table 3 Sensitivity of cost to load factor

Fuel	Capture	60% Load Factor (c/kWh)	$/t CO_2 avoided	35% Load Factor (c/kWh)	$/t CO_2 avoided
Coal	None	6.7		10.1	
	Post-combustion	9.3	40	14.2	63
Gas	None	6.7		7.8	
	Post-combustion	8.6	59	10.5	85

COSTS OF TRANSPORT AND STORAGE OF CO_2

The costs of transporting and storing CO_2 are influenced largely by local conditions. For example, if the CO_2 is used for EOR, the extra oil recovered can be worth more than the cost of the CO_2. However, if CO_2 capture and storage is used widely, the CO_2 may be stored in disused hydrocarbon fields or deep saline formations, and so no revenue would be generated. It is thought that the average costs of CO_2 transport and storage may be range from about 4-12$/t, depending on the injection technology and the properties of the storage reservoir.

A cost of 10 $/t$CO_2$ stored increases the cost of electricity production by about 0.8 c/kWh for coal-fired power plants and by about 0.4 c/kWh for gas-fired plants. The cost is greater for coal-fired plants because more than twice as much CO_2 is captured per kWh of net electricity.

OTHER FACTORS THAT INFLUENCE THE CHOICE OF TECHNOLOGY

The choice of power plant technology and CO_2 capture method will depend on many factors besides cost and efficiency, as has already been indicated. The focus of this section is on some of these other influences.

COAL COMPOSITION

The cost and performance of power plants depends on the coal composition. The data in this report are based on a bituminous coal described in the Annex. If low rank coal is the fuel selected, this will have a major impact on the power generation technology and the CO_2 capture process. The low rank coals are sub-bituminous, lignite and brown coal. They have relatively high moisture and oxygen contents and low heating values. Low rank coal accounts for almost half of the world's proven recoverable coal reserves on a mass basis and 30% of coal production. About 60% of the low rank coal reserves are sub-bituminous and the rest is lignite. The slurry feed IGCC technology evaluated by IEA GHG is not suitable for lignite because the water content of the slurry would be excessive. Studies by IEA GHG and others indicate that post combustion capture and oxy-combustion become more competitive relative to IGCC for lower rank coals. The coal sulphur content and the ash content and composition can also have a major impact on the relative merits of technologies.

OTHER FACTORS

The studies that have been discussed assessed some of the main criteria that would affect a utility's choice of power generation and CO_2 capture technology. There are, of course, a range of other criteria to be considered, including:

- the operating flexibility of the plant and its compatibility with future grid requirements;
- the risks of underperformance;
- various health and safety issues;
- the availability and diversity of equipment and technology suppliers;
- the compatibility of the new system with utilities' operating experience; and
- the potential for future improvements.

These additional criteria are being studied by the IEA GHG.

DISCUSSION AND CONCLUSIONS

Coal-fired power plants have increased steadily in efficiency and emissions reduction. A state of the art coal-fired power plant operates at an efficiency of around 45% and can incorporate the following facilities to reduce emissions:

- the catalytic removal of NO_x;
- ESP or bag filtration for the separation of particulates;
- capture of SO_x with wet or dry scrubbing; and
- the removal of mercury and heavy metals.

In this report the emphasis is on the reduction of CO_2 emissions. Technologies are available to reduce these by around 90%. The cost of power generation with CO_2 capture depends on a range of technical and economic factors, including the extremely variable cost of fuel. However, the cost of power generation, with CO_2 capture included, is estimated to be around 7-8 c/kWh (US), based on typical current European fuel prices.

PF combustion and NGCC are the most widely used power generation technologies and IGCC technology is being demonstrated in commercial scale plants.

CO_2 produced by the combustion of coal or gas can be captured in different ways:

- post-combustion using a formulated amine solvent;
- pre-combustion for gasification processes, using selective regenerative chemical and physical solvents; and
- oxy-combustion.

Post-combustion processes are unproven on the large scale required by the power industry. Questions remain about the rate of solvent deterioration. Capital and energy demands are high. Thus, technological developments are desirable, and are likely to happen if the pressure to capture CO_2 increases.

Pre-combustion CO_2 capture processes are more proven but the basic power generation process (IGCC) is less well proven than PF. The main issues are the integration, operability and reliability of plants. The processes also consume large amounts of capital and energy. So again, improvements are sought.

The third route to capture CO_2 is by oxy-combustion. Oxy-combustion development is in the early stages. There is interest in oxy-combustion as it enables power to be produced, with nearly zero emissions of greenhouse gases. However, the cost of oxygen production in sufficient quantity is a major penalty.

IEA GHG studies have found that the thermal efficiencies of power plants with CO_2 capture, based on the leading technologies are 32-35% (LHV) for bituminous coal-fired plants and 45-50% for natural gas combined cycle plants. The studies considered in this report have assessed some of the main general criteria which affect a utility's choice of power generation and CO_2 capture technology. But local circumstances and utilities' preferences will also influence the choice of power generation and CO_2 capture technology.

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2006/1 CO_2 Capture in Low Rank Coal Power Plants. January 2006

2006/8 CO_2 Capture as a Factor in Power Station Investment Decisions. May 2006

ANNEX

The capture techniques were studied for the IEA GHG by a number of leading engineering contractors and developers:

- post-combustion capture was studied by Fluor, in collaboration with Mitsui Babcock and Alstom, and by MHI;
- pre-combustion capture was studied by Foster Wheeler, with data from gasification and gas treating vendors; and
- oxy-combustion was studied by Mitsui Babcock, in collaboration with Air Products and Alstom.

The technical and economic specifications for the power plant used in the assessments are listed below.

TECHNICAL CRITERIA

Coal feed	Australian bituminous coal	
	Ash	12.2% as received
	Moisture	9.5% as received
	Carbon	82.5% dry ash free
	Hydrogen	5.6% dry ash free
	Oxygen	9.0% dry ash free
	Nitrogen	1.8% dry ash free
	Sulphur	1.1% dry ash free
	Chlorine	0.03% dry ash free
	LHV	25.87 MJ/kg as received
Natural gas	Southern Norwegian North Sea	
	Methane	83.9 vol%
	Ethane	9.2 vol%
	Propane	3.3 vol%
	Butane+	1.4 vol%
	CO_2	1.8 vol%
	N_2	0.4 vol%
Plant location	Netherlands coastal site	
	Average air temperature	9°C
	Average sea water temperature	12°C
CO_2 output pressure	11 MPa	

ECONOMIC CRITERIA

DCF rate	10% per year, excluding inflation
Plant operating life	25 years
Plant construction	3 years
Load factor	85%
Coal price	2.2 $/GJ (LHV)
Natural gas price	7.8 $/GJ (LHV)

The CO_2 is compressed to 11 MPa, as listed above. At this pressure it is a dense phase liquid which can be transported. However, the means of transport of the CO_2 and the nature of the storage reservoir will determine the amount of compression needed for the CO_2. It could be pumped to a higher pressure if required, with little impact on the plant performance and cost. It could also be liquefied for transport by ship if required.

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Storing CO_2 Underground

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

Disclaimer

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Date published : May 2007

Cover Picture : Photograph of sandstone from deep underground in Canada magnified over 100 times. This is the type of rock that could be used for CO_2 storage - the CO_2 becomes trapped in the pore spaces (highlighted in blue) between the grains of rock.

CONTENTS

INTRODUCTION

Carbon dioxide (CO_2) is the main cause of global warming and the level of CO_2 in the earth's atmosphere is rising as a result of human activities. Experts agree that a range of actions will have to be taken soon in order to reduce the amount of CO_2 entering the atmosphere. Part of the solution could be to capture millions of tonnes of CO_2 produced by industrial processes and store the CO_2 deep underground - this is known as CO_2 Capture and geological Storage (CCS). This booklet explains the geological storage of CO_2 and answers the most frequently asked questions:

- Can CO_2 be stored deep underground?
- What difference could CCS make to global warming?
- How can CO_2 be captured from industry?
- Where can CO_2 be geologically stored?
- Why does CO_2 stay underground?
- Where are the good geological storage sites?
- Where is CO_2 geological storage happening today?
- What is the future of CO_2 geological storage?

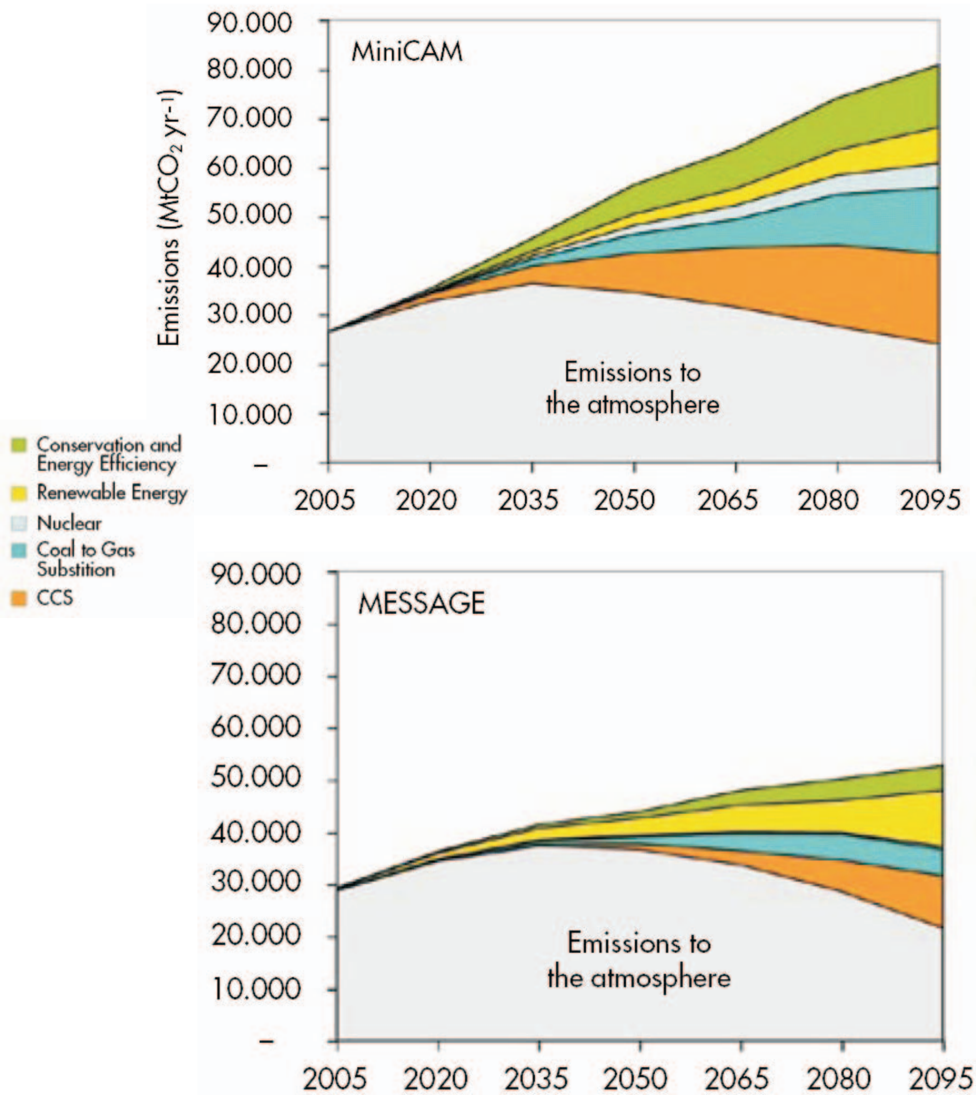
More detailed information is available from the United Nations Intergovernmental Panel on Climate Change (IPCC) Special Report on Carbon Dioxide Capture and Storage (www.ipcc.ch).

CAN CO_2 BE STORED DEEP UNDERGROUND?

Several projects are already storing millions of tonnes of CO_2 underground and many more are now being planned (see pages 10 and 11 for details). Oil and gas companies have many decades experience of storing natural gas deep underground and using CO_2 in oilfields, to 'push' oil towards producing wells - a technique known as Enhanced Oil Recovery (EOR). The success of these projects provides a great deal of confidence in the potential to store large quantities of CO_2 underground - safely and securely. Using CCS on an industrial scale to reduce CO_2 emissions involves adapting technologies that already exist and are widely used by several industries (such as fertilizer manufacture and oil production).

WHAT DIFFERENCE COULD CCS MAKE?

The IPCC graphs below show the vital role that CCS could play to help reduce CO_2 emissions during this century (along with other techniques such as renewable energy and improved energy efficiency). In each case, CCS contributes around a quarter of the emissions reduction required to control global warming.



Illustrative examples of the potential global contribution of CCS based on two alternative integrated assessment models (MESSAGE and MiniCAM) from the IPCC Special Report on Carbon Dioxide Capture and Storage

HOW CAN CO_2 BE CAPTURED FROM INDUSTRY?

CCS involves capturing the CO_2 produced by the burning of hydrocarbons (such as natural gas and coal) before it enters the atmosphere, and storing it deep underground in rock formations where it would remain indefinitely. CCS is most cost-effective when applied to large, stationary sources of CO_2 (such as power stations and steelworks), which account for more than half of all man-made CO_2 emissions. The CO_2 can be captured from hydrocarbons before, during or after burning and the technology to do this is already widely used in many industries (such as gas processing and fertiliser production).The illustrations below show the three methods of capturing CO_2 – applied to a gas-fired power station.

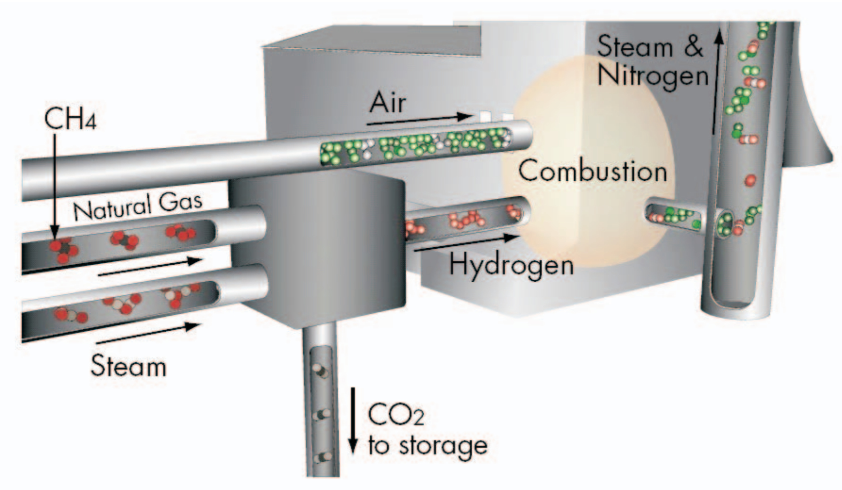


Figure 1 Before burning - Pre-combustion capture
(Figures 1-3 Courtesy of the CO_2 Capture Project)

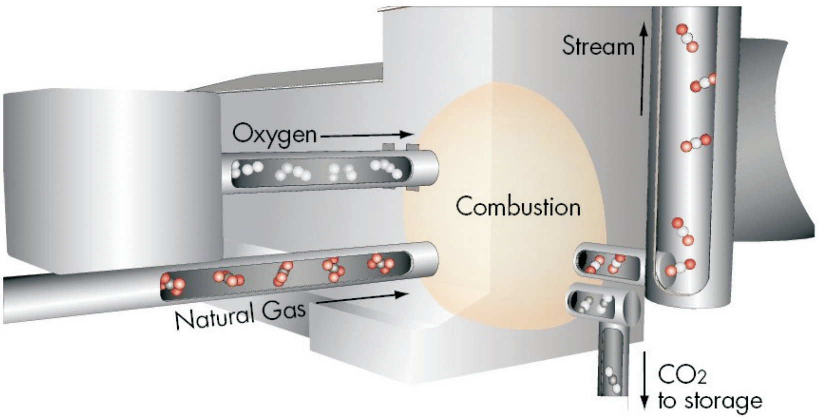


Figure 2 During burning - Oxyfuel capture

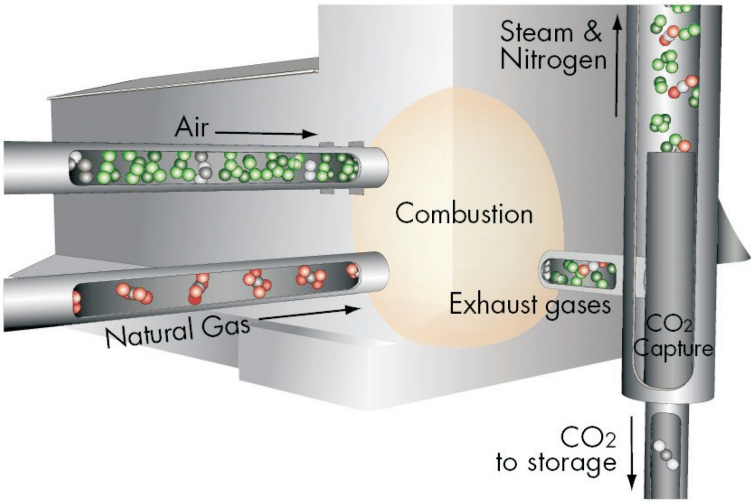


Figure 3 After burning - Post-combustion capture

One of the advantages of capturing the CO_2 before burning (pre-combustion capture) is that this technique separates hydrogen from hydrocarbon fuels. Hydrogen is a 'clean' fuel, producing only water when burned. Another possibility is to use CCS with biomass fuels (such as crop residues). Plants capture CO_2 from the atmosphere (by photosynthesis) but when they die, most of that CO_2 is returned to the atmosphere. Capturing and geologically storing the CO_2 produced from burning biomass would represent the opposite of today's fossil fuel economy – permanently removing CO_2 from the atmosphere and storing it deep underground.

WHERE CAN CO_2 BE GEOLOGICALLY STORED?

The best rocks for CO_2 storage are depleted oil and gas fields and deep saline formations. These are layers of porous rock (such as sandstone) over 1km underground (either on land or far below the sea floor), located underneath a layer of impermeable rock (known as a cap-rock) which acts as a seal. In the case of oil and gas fields, it was this cap-rock that trapped the oil and gas underground for millions of years.

Depleted oil and gas fields are the best places to start storing CO_2 because their geology is well known and they are proven traps.

Deep saline formations are rocks with pore spaces that are filled with very salty water (much saltier than seawater). They exist in most regions of the world and appear to have a very large capacity for CO_2 storage. Currently the geology of saline formations is less well understood than for oil and gas fields so more work needs to be done to understand which formations will be best suited to CO_2 storage.

The photograph below shows a sandstone that would be suitable for geological storage of CO_2.

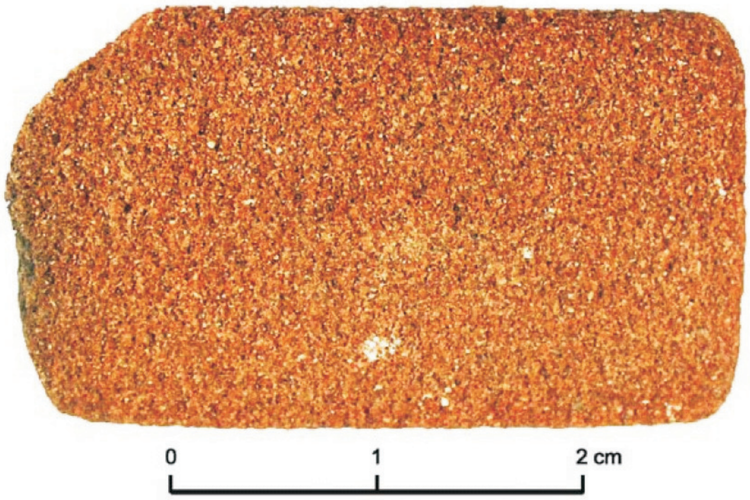


Figure 4 Sandstone, typical of the type of rock that would be suitable for geological storage of CO_2

Many natural geological stores of CO_2 have been discovered underground (often by people looking for oil and gas). In many cases the CO_2 has been there for millions of years. In other situations (volcanoes, geysers), CO_2 does leak naturally from underground. Indeed the world's natural carbonated mineral waters, long prized and bottled for drinking, come from natural CO_2 sources. The reasons why some rock formations trap the CO_2 permanently and some do not are well understood and this understanding can be used to select and manage storage sites to minimise the chance of leakage.

Potential storage sites will need to be carefully selected and managed in order to minimise any chance of CO_2 leakage. Once the CO_2 has been placed in the storage location, the wells will have to be sealed to ensure that the CO_2 stays in place. On the surface, air and soil sampling can be used to detect potential CO_2 leakage whilst changes deep underground can be monitored by detecting sound (seismic), electromagnetic, gravity or density changes within the rock formations.

WHY DOES CO_2 STAY UNDERGROUND?

As CO_2 is pumped deep underground it is compressed by the higher pressures and becomes essentially a liquid, which then becomes trapped in the pore spaces between the grains of rock by several means, summarised below. Depending on the physical and chemical characteristics of the rocks and fluids, all or some of these trapping mechanisms will take place. Structural storage has immediate effect, the others take time, but provide increased storage security. The longer the CO_2 remains underground, the more securely it is stored.

Structural Storage

When the CO_2 is pumped deep underground, it is initially more buoyant than water and will rise up through the porous rocks until it reaches the top of the formation where it can become trapped by an impermeable layer of cap-rock, such as shale. The wells that were drilled to place the CO_2 in storage can be sealed with plugs made of steel and cement. Figure 6 is an illustration of the In Salah Methane gas for electricity generation project in Algeria, where 1 million tonnes of CO_2 per year (equivalent to the emissions from a quarter of a million cars) is being stored in a producing gas field. The natural gas produced from the deep rock formations is a mixture of methane (CH_4) and CO_2. Once it reaches the surface, the natural gas is separated into methane (which is piped to a power plant for electricity generation) and CO_2 (which is pumped back into the deep rock formations for storage). The cap-rock that kept the natural gas in the rock formation for millions of years keeps the liquid CO_2 stored in the underground reservoir.

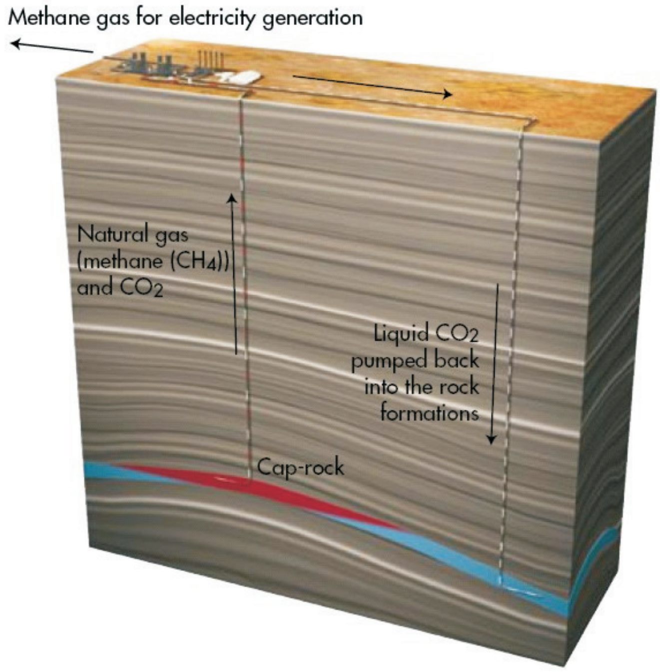
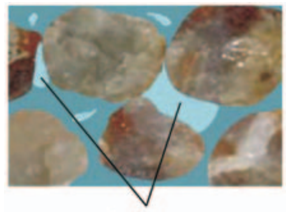


Figure 6 The In Salah CO_2 Storage Project in Algeria

Residual Storage

Reservoir rocks act like a tight, rigid sponge. Air in a sponge is residually trapped and the sponge usually has to be squeezed several times to replace the air with water. When liquid CO_2 is pumped into a rock formation, much of it becomes stuck within the pore spaces of the rock and does not move. This is known as residual trapping.



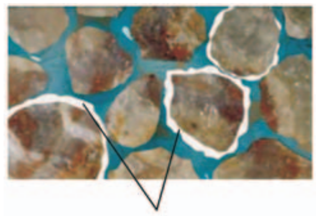
Residual trapping of CO_2

Dissolution Storage

CO_2 dissolves in salty water, just like sugar dissolves in tea. The water with CO_2 dissolved in it is then heavier than the water around it (without CO_2) and so sinks to the bottom of the rock formation, trapping the CO_2 indefinitely.

Mineral Storage

CO_2 dissolved in salt water is weakly acidic and can react with the minerals in the surrounding rocks, forming new minerals, as a coating on the rock (much like shellfish use calcium and carbon from seawater to form their shells). This process can be rapid or very slow (depending on the chemistry of the rocks and water) and it effectively binds the CO_2 to the rocks.



Mineral trapping of CO_2

WHERE ARE THE GOOD GEOLOGICAL STORAGE SITES?

The map below (Figure 7) shows the location of the best rocks for CO_2 storage based on our current knowledge. Total global man-made CO_2 emissions are currently around 24 gigatonnes of CO_2 per year. The CO_2 storage capacity of hydrocarbon (oil, gas and coal) reservoirs is estimated to be around 800 gigatonnes of CO_2. The world's deep saline formations may have a much greater storage capacity than depleted oil and gas fields, although more work needs to be done to assess their full potential for CO_2 storage.

Figure 7   Map showing rocks categorised as highly prospective for CO_2 storage, from the IPCC Special Report on Carbon Dioxide Capture and Storage

WHERE IS CO_2 GEOLOGICAL STORAGE HAPPENING?

Several large-scale geological storage projects are already in operation, and many more have been proposed. The map below (Figure 8) shows the locations of existing and proposed CO_2 storage projects, along with the locations of projects where CO_2 is currently used to enhance oil and gas recovery.

Figure 8 Location of sites where geological storage of CO_2 and CO_2-enhanced oil and gas recovery takes place, from the IPCC Special Report on Carbon Dioxide Capture and Storage

WHAT IS THE FUTURE OF CO_2 GEOLOGICAL STORAGE?

The illustration below (Figure 9) shows a CCS project, planned in California that would generate low-carbon electricity using hydrogen manufactured from petroleum coke and store the resultant CO_2 in a nearby mature oil field. This project would generate up to 500 MW low-carbon electricity (enough to power a third of a million homes) and is planned to be operating by 2012. Using CO_2 capture and storage at 700 large power plants would be equivalent (in CO_2 terms) to eliminating all the cars on the planet today.

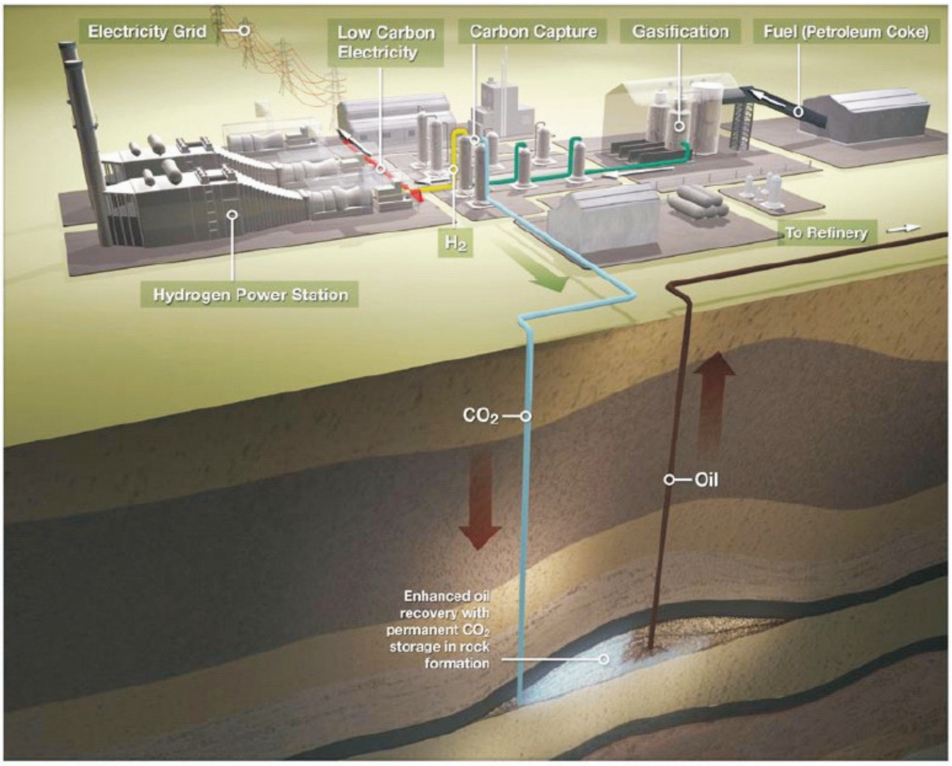


Figure 9 Illustration of a planned power plant in California with CCS. Illustration courtesy of BP and Edison Mission Group)

CONCLUSIONS

CO_2 capture and geological storage could contribute a significant part of the solution to the global warming problem. The required technology has been used by the oil and gas industry for many years – it is proven and available today. CCS could therefore play a significant role in helping to reduce CO_2 emissions over the coming decades. However, CCS is a relatively new concept and therefore not specifically addressed by most laws and regulations (both globally and locally).

Commercial organisations will invest in CCS projects when they are legal and financially viable. In order for CCS to be implemented on a widespread scale, work needs to be done soon to develop appropriate regulations and commercial frameworks for CCS.

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Natural Releases of CO_2

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Cover image taken by Alexandre Halbwachs.

The cover image shows Lake Nyos, Cameroon with degassing operations underway.

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CONTENTS

INTRODUCTION

THE NEED TO ENSURE SECURITY OF CO_2 STORAGE

Increasing concentrations of CO_2 in the Earth's atmosphere are enhancing global warming and subsequent climate change. One option for reducing anthropogenic CO_2 emissions to the atmosphere is the deployment of technologies for the capture and storage of CO_2 produced by the combustion of fossil fuels. This option, however, would be deployed as part of a portfolio of measures, including renewable energy, nuclear power, fuel switching and energy efficiency. The technology for capturing CO_2 from power plant is already available and could lead to significant reductions in CO_2 emissions, providing options are available for disposing of the captured CO_2. One of the most attractive methods being considered, which offers potential long-term containment of significant quantities of CO_2, is geological storage.

Geological storage of anthropogenic CO_2 involves injecting the CO_2 underground, for example in depleted oil and gas reservoirs, deep saline reservoirs and unminable coal seams, where it becomes secured in a similar way to hydrocarbons that have remained naturally trapped in gas and oil fields for millions of years.

Storage of CO_2 in gas or oil reservoirs is currently being demonstrated at a commercial scale at a number of sites. For example, since 1996 the Sleipner project has been capturing CO_2 from the natural gas extracted from the Sleipner West gas field in the North Sea and reinjecting it into a deep saline formation above the gas field.

Concerns have been expressed that if CO_2 capture and storage becomes widely deployed possible seepage from these underground storage sites could have a deleterious effect on the environment. These concerns have arisen largely because, over the past few decades, a few natural events involving the rapid emissions of large masses of CO_2 in volcanic areas have resulted in serious incidents.

To understand the circumstances that lead to these natural release incidents, the IEA Greenhouse Gas R&D Programme commissioned eminent geologists from the British Geological Survey and CRIEPI in Japan to provide a factual and balanced overview of natural CO_2 releases from underground sources and their relevance to geological CO_2 storage. This report provides a summary of their findings.

IEA GREENHOUSE GAS R&D PROGRAMME

This report has been produced by the IEA Greenhouse Gas R&D Programme (IEA GHG). IEA GHG is an international collaboration of governments and industries from many countries with several linked objectives:

- To identify and evaluate technologies that could be used to reduce the emissions of greenhouse gases arising from the use of fossil fuels;
- To disseminate the results of those evaluations;
- To identify targets for research, development and demonstration, and promote the appropriate work.

IEA GHG was established in 1991 and, since then, its main focus has been on capture and storage of CO_2. It has also examined a wide range of other technologies, including carbon sequestration in forests, renewable energy sources (biomass and wind energy) and methods for reducing emissions of non-CO_2 greenhouses gases. This helps to put in perspective the potential of capture and storage of CO_2.

NATURAL RELEASES OF CO_2

CO_2 EMISSIONS FROM VOLCANIC ACTIVITIES

The most important process by which naturally occurring CO_2 from underground sources can be emitted into the atmosphere is through the degassing of magma (molten rock) in volcanic areas. When magma rises towards the Earth's surface, the pressure on it is lowered and dissolved CO_2 is released. Most of the CO_2 originating from magma degassing is emitted through volcanoes and associated fissures, or hydrothermal sites.

Volcanic regions by their very nature are prone to eruptions, ground movement, earth tremors and explosions that can fracture the surrounding rocks. They may also contain magma chambers or voids that are capable of holding large volumes of gas (mostly water vapour) that can be suddenly released at high pressure as a result of these fractures.

Although CO_2 is also released rapidly from the central conduit(s) of volcanoes during violent eruptions. It has recently been recognised that non-eruptive diffuse degassing may be the principle mode of gas release from sites of both active and dormant volcanic activity. For instance around the Yellowstone hydrothermal area in the USA, diffuse degassing has been measured at 16 million tonnes CO_2 per year. In diffuse degassing, the CO_2 can percolate to the surface through porous zones on volcano flanks and through hydrothermal areas (Box 1).

Although they are not common, dormant or extinct volcanoes can also contain crater lakes; worldwide there are around 20-30 such examples.

Crater lakes are located at the top of volcanoes and are commonly surrounded by high crater walls. The lakes overflow down a spillway leading to a valley system. In tropical areas such lakes may be deep and still and the water column within them can become stratified, as there is little seasonal mixing of the lake waters. CO_2, or other gases percolating up highly permeable fissures and fractures into the crater lake floors can dissolve into the lower levels of the lake waters (increasing their density) until they become saturated with respect to CO_2.

BOX 1. AN EXAMPLE OF DIFFUSE DEGASSING

An eruption of Old Faithful, perhaps the world's best known geyser and a major tourist attraction, rises above Yellowstone's Upper Geyser Basin.

Yellowstone is the site of one of the world's largest hydrothermal systems and contains a number of different types of hydrothermal features; all of which release CO_2 by means of diffuse degassing. Geysers occur when CO_2-charged heated water rising from deep within the ground is released periodically and explosively. With hot springs, the water charged with CO_2 is released at a steady, non-explosive rate, whereas with mud pots (sometimes known as mud volcanoes) CO_2 release occurs through clayey mud. (Image courtesy of Smithsonian Institution)

BOX 2. THE DIENG INCIDENT

The Dieng incident was associated with a phreatic explosion that resulted in the formation of a new crater and the reactivation of a pre-existing fracture. Phreatic explosions normally release large volumes of superheated water with only small amounts of CO_2. It was considered that the pure gaseous CO_2 released must have accumulated in a shallow reservoir as a high density fluid before the explosion and was then released through fractures as they opened up due to the pressure build-up in the volcano prior to the explosion. (Image courtesy of Sumarma Hamidi, Volcanological Survey of Indonesia).

BOX 3. LAKE NYOS AND LAKE MONOUN INCIDENTS

Lake Nyos (image above after the CO_2 release) and Lake Monoun are both tropical crater lakes at considerable elevation compared to much of the surrounding topography. The lakes are not seasonally overturning and, due to low-level volcanic activity, springs in the lake bottoms are constantly supplying CO_2 to the bottom of the lakes. This dissolves in the lake water and results in a layer of dense, CO_2-saturated water building up above the bottom of the lake. At Lake Monoun an earthquake is thought to have upset the density stratification of the lake, whereas at Lake Nyos, geologists are uncertain what triggered the sudden release of CO_2; although some suspect a landslide. Whatever the cause, the event resulted in the rapid mixing of the CO_2 supersaturated deep water with the upper layers of the lake, where the reduced pressure allowed the stored CO_2 to effervesce out of solution leading to the sudden release of CO_2 from the crater lake. The cold CO_2 was confined by the crater walls and flowed down into adjoining valleys suffocating people and animals before it could dissipate.

become saturated with respect to CO_2. Once saturated, any disturbance that causes part of the lower lake waters to rise could cause CO_2 to come out of solution. Only a very few, like those at Lake Nyos and Lake Monoun in Cameroon (see below), have become saturated with CO_2. In contrast, the lakes commonly found in temperate regions are seasonally overturning and therefore pose much less potential danger from CO_2 build up, should it occur.

Impact of CO_2 emissions from volcanic activities

The impact of natural CO_2 emissions from volcanic activities on the environment is mainly dependent on the scale and location of the incident. Although CO_2 is non-toxic, a large rapid release of the gas is of concern because CO_2 is an asphyxiant. There are a small number of examples of natural disasters in volcanic areas caused by sudden emissions of large volumes of CO_2 that have led to loss of life.

One of these incidents occurred at the Dieng volcano complex in Indonesia and provides an example of the danger presented by sudden CO_2 emissions from volcanoes following a build-up of gas within them. In 1979, at the Dieng complex, diffusive CO_2 emissions occurred prior to a major eruption. About 200 000 tonnes of pure CO_2 was released and flowed from the volcano to the plain below as a dense layer resulting in the asphyxiation of 142 people (see Box 2).

The two other recorded disasters, however, were associated with sudden emissions of CO_2 from volcanic crater lakes at Lake Nyos and Lake Monoun, both of which are in Cameroon in West Africa (see Box 3). When Lake Monoun overturned in 1984, the sudden release of volcanic CO_2 led to the death of 37 people. In a similar incident at nearby

BOX 4. DIFFUSE DEGASSING AT MAMMOTH MOUNTAIN

Tree kill on the shore of Horseshoe Lake, Mammoth Mountain, California, was caused by CO_2 emerging through the ground along fault zones on the volcano's flanks, following a period of enhanced seismic activity. The gray area in bottom centre of the photo marks the location of trees killed by high concentrations of carbon dioxide gas in the soil. (Photograph by S.R. Brantley)

Lake Nyos in 1986, approximately 1.24 million tonnes of CO_2 was released from the lake in just a few hours and asphyxiated 1700 people. These releases, however, involved a set of specific geographical features and geological processes that contributed to each event and the loss of life that followed.

In addition to these major incidents, there have been a number of smaller incidents that can be attributed to natural CO_2 releases and which have lead to asphyxiation of animals and damage to plant life. In volcanic areas, diffuse degassing of CO_2 is commonplace. The CO_2 normally mixes with air, dissipates rapidly and generally is not considered to be hazardous to man. However, if the dispersion is restricted or there is a sudden increase in seismic activity, high concentrations of CO_2 can accumulate. Notable examples include the diffuse degassing of CO_2 through soil on the flanks of Mammoth Mountain, California, which resulted in localised ecosystem damage (see Box 4) and the sudden release of CO_2 in the Cava dei Sielci region of the Alban Hills volcanic complex in Italy, which resulted in the deaths of more than 30 animals. Both were associated with an increase in seismic activity in the area.

CO_2 EMISSIONS FROM SEDIMENTARY BASINS

CO_2 also occurs as a result of geological processes in large, sometimes high purity (>90% CO_2) reservoirs in many sedimentary basins. Sedimentary basins are widely spread around the world and many occur in tectonically stable regions, where there is little or no volcanic/hydrothermal activity.

CO_2 is commonly trapped within the porous and permeable reservoir rocks as a supercritical phase (a highly compressed gas) but may also dissolve in any salt water remaining in the rock formation. An overlying impermeable cap rock is often present which acts as a natural seal, in a similar manner to the presence of oil and natural gas fields in sedimentary basins. Naturally occurring CO_2 may also be retained in other geological settings, for example, confined in the pore spaces of sedimentary rocks folded into domes or other structures.

The best documented natural CO_2 field, as well as the worlds' largest supply of commercially traded CO_2, is the McElmo Dome in Colorado. The CO_2 reservoir is capped by over 700m of impervious salt, shale and sandstone which provides an effective seal and, at the time of discovery in 1948, contained an estimated 1.6 billion tonnes of high purity CO_2. A further notable example is the giant CO_2 field in the Pisgah Anticline, Mississippi, USA which is thought to be around 65 million years old and holds over 200 million tonnes of CO_2.

Mofettes are openings in the earth's surface from which carbon dioxide and other gases escape. The mofettes pictured here, where bubbles of gas constantly rise to the surface, is in the nature reserve Soos near Frantiskovy Lazne, Czech Republik. Image courtesy of André Künzelmann/UFZ

The Bublák mofette in the Eger Basin, Czech Republik. Here, the gas rises spontaneously from the earth's mantle to the surface and is more than 99 per cent CO_2. Image courtesy of André Künzelmann/UFZ

CO_2 leaks from sedimentary basins can occur through permeable rock and/or along any faults or fissures in the rock, although CO_2 can also be accidentally emitted from via boreholes. In some areas CO_2 leakages along faults can result in CO_2 charged groundwater emerging visibly in springs and through old well bores. More typically, however, CO_2 appearing at the ground surface is already dispersed to the surrounding strata, so that it emerges at very low seepage rates and over a larger area than that of the point of origin.

In offshore areas the migration of gases through the seabed commonly produces pockmarks or, where gases emerge along with mud, a mound on the sea floor called a mud volcano. Mud volcanoes may also occur onshore. The best documented natural CO_2 emission from the sea bed occurs in the Tyrrhenian Sea offshore from the Aeolian Islands in Italy. Here 25,000 tonnes of CO_2 per year are released over an area of 15km^2, most of which dissolves into the sea water.

Impact of CO_2 emissions from sedimentary basins

There are numerous natural CO_2 fields within sedimentary basins around the world some of which, due to the presence of an overlying impermeable cap rock, have held CO_2 for millions of years without evidence of leakage or environmental impact. Many others, however, do leak although there are no recorded incidents involving sudden large emissions of CO_2 from sedimentary basins. Leakage generally manifests itself as carbonated springs or dry seeps and can result in very localized ecosystem damage.

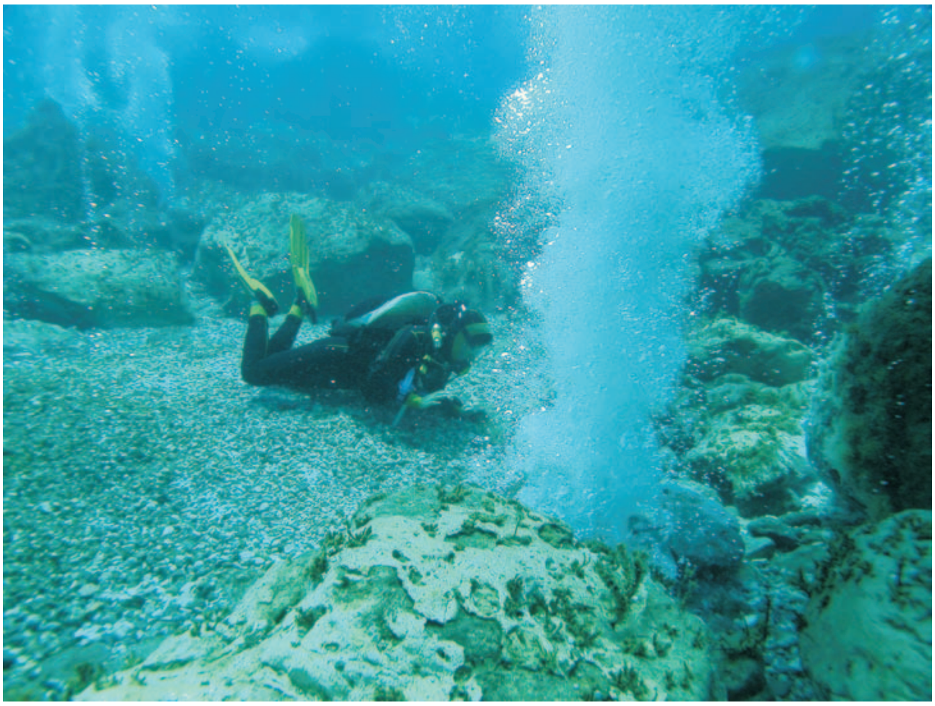
The environmental impact resulting from these leaks is significantly smaller than those occurring in volcanic regions. They depend ultimately on many factors that control the migration and accumulation of this gas. In many cases CO_2 emissions through the ground are not a significant hazard to man because they are dispersed by the wind. The main threat to man is where CO_2 is emitted in situations where it can build up to high concentrations, for example in buildings or in hollows in the ground. Leakages are more likely to have an adverse impact on vegetation, killing it or damaging it depending on the levels of CO_2 released.

There are a number of notable examples of CO_2 emissions from sedimentary basins which present, at most, only very local hazards to man or the natural environment. These include the Southeast Basin in France where several small CO_2 fields are located along major fault systems. The CO_2 dissolves in the groundwater and emerges in carbonated springs, many of which are exploited by the sparkling mineral water industries, such as Badoit, Vichy and Perrier.

The Colorado Plateau is also an interesting example because it contains both major CO_2 fields and areas where CO_2 is leaking. In some areas, such as the Paradox Basin, CO_2 seepage along faults results in CO_2 charged groundwater in several springs and through old well bores. The Crystal Geyser is a dramatic example of leakage along a well bore, which has since become a tourist attraction. The geyser first erupted in 1935 when a well being drilled intersected a CO_2-charged aquifer. Today the geyser erupts every 4 to 12 hours as a result of pressure changes in the aquifer.

Mátraderecske in northern Hungary provides an example of CO_2 leakage as a result of the presence of permeable caprocks above CO_2 fields. High levels of CO_2 have been recorded for some time in this area; however, in 1992 residents in two houses in the village suffered from headaches and since then control flushing systems have been installed.

The impacts of CO_2 emissions in off-shore areas are not well known. CO_2 may emerge at the seabed dissolved in water or as a free gas. If in a free gas phase it may form a train of bubbles that will rise through the water column and is unlikely to build up in high concentrations; although unless the emission rate is very high, the CO_2 is more likely to dissolve in the water column. The dissolution of CO_2 into seawater lowers its pH (increases its acidity), at least locally, and may impact on the marine environment, depending on the dispersion and duration of emissions.



This is the strongest vent in the Panarea degassing field. The average depth is around 10 meters and the seafloor is characterized by a gravel cover. The position is very close to the north point of the Bottaro islet. Image courtesy of Giorgio Caramanna, University La Sapienza, Roma

GEOLOGICAL STORAGE SITES FOR ANTHROPOGENIC CO_2

Geological storage of CO_2 involves injecting the CO_2 underground, such that it becomes trapped in the pore spaces between grains of sedimentary rock in exactly the same way that hydrocarbons are naturally trapped in oil and gas fields. The procedure offers the opportunity to remove large quantities of CO_2 to an underground storage site, using techniques that are both currently available and constantly improving.

ENVIRONMENTAL CONCERNS

Significant quantities of CO_2 are already injected underground around the world in enhanced oil recovery projects. Underground storage of natural gas, an analogous technique, is also widely practised. Nevertheless, because CO_2 is an asphyxiant and heavier than air, there may be concerns about the safety of underground CO_2 storage, either from possible slow seepage or sudden large-scale emission resulting from well failure. Slow seepage is unlikely to give cause for safety concerns unless the gas is inadvertently trapped. The risk of sudden large-scale release of CO_2 would have to be avoided in the same way as for other gases, such as by avoiding unsuitable sites. It is also important that CO_2 remains in the underground storage sites for a long period of time (up to 1000 years) to minimise climate change.

DEVELOPING CO_2 STORAGE SITES

Sites for the geological storage of anthropogenic CO_2 are most likely to be situated in stable sedimentary basins because storage sites will need to be contained in tectonically stable locations with a reasonable storage capacity. Depleted oil and gas reservoirs, in particular, have a number of attractive features as CO_2 storage reservoirs:

- the reservoirs are proven traps, known to have held liquids and gases for millions of years;
- the reservoirs have well known geology;
- a large number of potential sites exist, as thousands of oil and gas fields are approaching the ends of their economically productive lives; and
- exploration costs would be small.

Geological storage of CO_2 can be considered as closely analogous to natural CO_2 fields that occur in sedimentary basins. CO_2 storage sites would need to be sited at carefully selected locations, to take advantage of the geological factors that prevent gas leakage. For a storage operation to earn a permit, regulators would want assurance that any potential gradual CO_2 seepage would only occur at a very slow rate, that sudden releases are extremely unlikely and that any seeps cannot migrate to belowground confined spaces that are vulnerable to sudden release.

The regulatory process is likely to include:

- a rigorous characterisation of the storage site and surrounding area;
- the construction of geological models of the site and surrounding area;
- the simulation of CO_2 injection into the storage reservoir;
- a risk evaluation/management process
- monitoring of the stored CO_2.

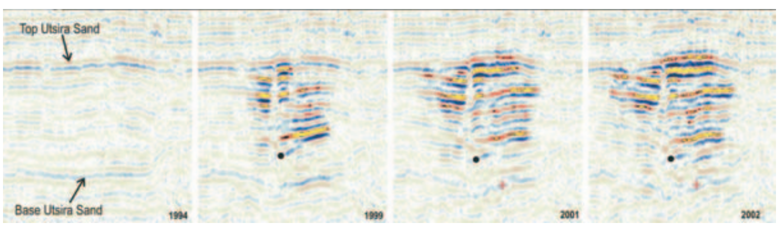
To cover the unlikely event that seepage might occur a remediation plan will also likely to be required. If the potential for seepage is identified a remediation plan may be required. During the site characterisation, any concerns over the integrity of the rock cap and its ability to contain CO_2 for the necessary timescales would need to be addressed. During CO_2 injection, monitoring and modelling of the site would be required to provide information needed to demonstrate the selected sites ability to contain CO_2 for the necessary timescales.

CO_2 STORAGE PROJECTS

There are a number of current geological CO_2 storage operations being undertaken worldwide. Many of the first CO_2 storage sites were old oil fields where CO_2 could be injected to boost production of crude oil (known as CO_2 enhanced oil recovery or CO_2-EOR). More recently, underground CO_2 storage is being performed at gas production sites, where raw natural gas produced at the site contains too much CO_2 for commercial use, so the excess is removed, compressed and then injected underground. Examples of such projects that are undergoing detailed monitoring of the surface and subsurface include the Sleipner project in the North Sea and the CO_2-EOR projects at Weyburn in Saskatchewan, Canada and Rangely, in Colorado, USA.

At the Sleipner gas field CO_2 is injected under pressure into the Utsira formation, which is a saline-water-saturated sandstone formation extending under a large area of the North Sea at a depth of about 800m. Approximately 1 million tonnes of CO_2 is removed annually from the raw natural gas and injected into the deep saline reservoir above the gas field. The CO_2 injection operation started in October 1996 and over the lifetime of the project, a total of 20 million tonnes of CO_2 is expected to be stored. The project has been closely monitored and no migration from the storage reservoir has been detected (see Box 5).

BOX 5. SEISMIC PROFILES OF THE SLEIPNER CO_2 INJECTION SITE



Time lapse seismic profiles through the Utsira Sand and CO_2 plume at the Sleipner CO_2 injection site acquired over the injection point (marked by a black dot) and storage area. The first was acquired in 1994, prior to any CO_2 injection. The subsequent surveys were taken as injection progressed between 1999 and 2002. The difference in reflectivity between the baseline survey (1994) and later surveys is due to the presence of CO_2 in the pore spaces of the reservoir rock.

The seismic profiles demonstrate that the CO_2 has spread out laterally from the injection point in a series of discrete layers. There is no evidence of faults or fractures in the cap rock above the injection site and no evidence that CO_2 is migrating out of the storage reservoir.

BOX 6. THE IEA GHG WEYBURN CO_2 MONITORING AND STORAGE PROJECT

The project has undertaken a comprehensive programme of sub-surface and surface monitoring. This has involved repeat seismic surveying, geochemical sampling of production fluids and soil gas sampling.

Soil gas sampling is designed to detect injected CO_2 that may have escaped from the reservoir and seeped to the surface. Sampling and analysis of gas above the injection site found fluxes for CO_2 and O_2 within the range of that for natural soils and comparable to an off-set reference location, indicating that there is no evidence so far for seepage of injected CO_2 from depth. Image courtesy of PTRC.

The Weyburn Project (Box 6) in Canada combines CO_2-EOR with a comprehensive monitoring and modelling programme to evaluate CO_2 storage. CO_2 injection commenced in 2000 and is anticipated that over the project lifetime some 20 million tonnes of CO_2 will be stored; currently 5 000 tonnes of CO_2 are injected daily. No leakage from the reservoir has been detected to date. Furthermore, long-term predictions indicate that the majority will remain permanently stored for 5000 years.

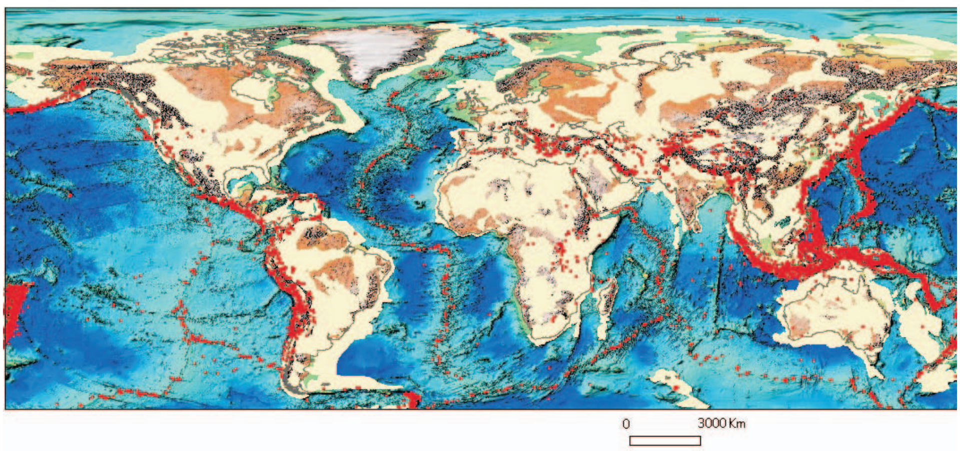
At the Rangely oil field in the USA around 23 million tonnes of CO_2 have been injected into the field since 1986. In 2000, a survey of the field and adjacent areas showed that CO_2 was emerging through the ground surface, albeit at very low seepage rates. Further investigations, however, suggest that this was largely due to the oxidation of methane originating from the oil reservoir or overlying strata, rather than leakage of injected CO_2.

RELEVANCE OF NATURAL CO_2 RELEASES TO GEOLOGICAL STORAGE

DISTINCTION BETWEEN NATURAL CO_2 RELEASES FROM SEDIMENTARY BASINS AND VOLCANIC AREAS

A major distinction can be made between natural CO_2 emissions that occur in volcanic areas and those that occur in sedimentary basins. Volcanic regions and associated hydrothermal areas, where natural emissions of CO_2 occur, are commonly tectonically unstable and may be liable to ground heave and fracturing. Moreover, because heat and steam are commonly present they can contain gas under great pressure, often in voids. The occasional large sudden emissions of CO_2 that have occurred in volcanic and hydrothermal areas are generally associated with seismic activity.

Volcanoes are located mainly around the Pacific rim, the east African rift, and the Atlantic ridge; the majority of the earth's surface is devoid of volcanic activity (see figure below).



Location of world earthquake centre. The red marks indicate earthquake centres above magnitude 5 for the previous 10 years. The yellow shading indicates high prospective or prospective areas. Courtesy of Geoscience Australia

By contrast, sedimentary basins are widely spread around the world and many occur in tectonically stable regions (see figure above). They commonly contain both porous/permeable reservoir rocks and impermeable cap rocks that can act as natural seals and prevent gases reaching the surface. The existence of natural barriers is proven by the presence of oil and natural gas fields in sedimentary basins.

RELEVANCE OF NATURAL CO_2 RELEASES

The major natural CO_2 emissions that have occurred can be regarded as representing fairly exceptional geological situations. These are either tropical craters lakes that do not seasonally overturn and are actively filling with CO_2 due to volcanic activity, or are the result of shallow CO_2 accumulations in voids or magma chambers (again originally from volcanic activity) that are released as a precursor to a volcanic eruption. Such geological situations have nothing in common with the stable sedimentary formations where it is proposed to store CO_2.

For example, at the Dieng volcano, the CO_2 was thought to have accumulated in a shallow reservoir as a high density fluid before the explosion and then released through fractures created due to the pressure build-up in the volcano prior to the explosion. This combination of large volumes of CO_2 gas in shallow reservoirs coupled with fracture development prior to an explosion would not occur in a sedimentary basin.

Similarly, the CO_2 releases at Lakes Nyos and Monoun were again the result of exceptional circumstances unlikely to be found at or near purpose designed CO_2 storage sites. These circumstances included the presence of stratified lakes at considerable elevation, the presence of a slow CO_2 leak into the bottom of the stratified lakes and the unobserved CO_2 saturation of the lower layer of the lake waters.

There are no recorded incidents involving sudden large emissions CO_2 from sedimentary basins. Seepage has been detected from some natural CO_2 fields along faults or as a result of boreholes, which in a few cases has resulted in very localized environmental damage. Although the environmental impact resulting from seepage are significantly smaller than those occurring in volcanic regions. With a rigorous site selection process, the risk of seepage occurring from geological storage sites in sedimentary basins can be minimised.

CONCLUSIONS

Geological storage offers the potential for long-term storage of significant quantities of CO_2. However, concerns over the security of underground storage of CO_2 have arisen largely because of a few natural events involving rapid emissions of large masses of CO_2 that have resulted in serious incidents.

The main incidents involving CO_2 emissions have all arisen in volcanically active regions and can be regarded as representing fairly exceptional geological situations.

Sites considered for geological storage of CO_2 are most likely to be situated in stable sedimentary basins and have nothing in common with the geological situations which resulted in the incidents that occurred in volcanic regions.

Seepages from natural CO_2 fields within sedimentary basins have been detected. However, any resulting ecosystem damage is generally localized and of modest impact. Some sedimentary basins have stored CO_2 for millions of years without any evidence of seepage.

Worldwide, there are a number of on-going geological CO_2 storage projects monitoring the fate of the injected CO_2 in geological formations which have given confidence in this option offering an effective solution for long term storage of significant quantities of CO_2.

Geologic Storage of Carbon Dioxide

STAYING SAFELY UNDERGROUND

IEA GREENHOUSE GAS R&D PROGRAMME

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International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Cooperation and Development (OECD) to implement an international energy programme. The IEA fosters cooperation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

IEA Greenhouse Gas R&D Programme

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CONTENTS

IEA GREENHOUSE GAS R&D PROGRAMME

EXECUTIVE SUMMARY

Geologic storage of carbon dioxide (CO_2) is the underground disposal of CO_2 from large industrial sources such as power plants. Carbon Capture and Storage (CCS), also known as Carbon Capture and Sequestration, includes geologic storage as one of its components.

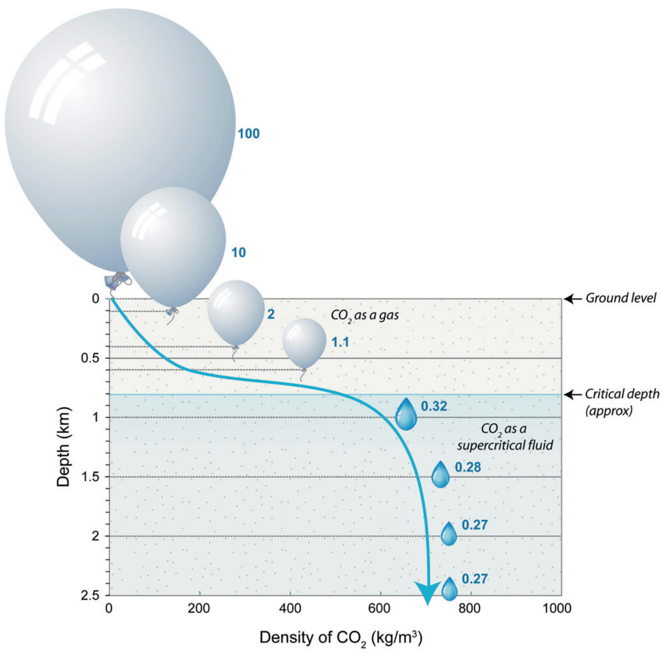
CCS is a powerful tool—along with energy efficiency, fuel switching and renewable energy sources—essential to reducing atmospheric CO_2 levels. Many studies show that the most effective and least-costly way to reduce CO_2 levels to avoid climate change is to use all CO_2 reduction tools, including CCS.

CO_2 is a natural substance in the air that is essential to life. As part of the natural carbon cycle, people and animals inhale oxygen from the air and exhale CO_2. Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere. CO_2 is also widely used for many purposes such as carbonating drinks and filling fire extinguishers. As a greenhouse gas, its presence in the atmosphere traps heat from the sun. Normally, this keeps the climate warm enough for life to continue. However, the burning of fossil fuels is increasing CO_2 levels in the atmosphere above naturally-occurring levels, contributing to global climate change.

In geologic storage, CO_2 is injected under high pressure into deep, stable rocks in which there are countless, tiny pores that trap natural fluids. Some types of rock formations have securely trapped fluids, including CO_2, for long periods, even millions of years. The CO_2 will be injected into these types of formations.

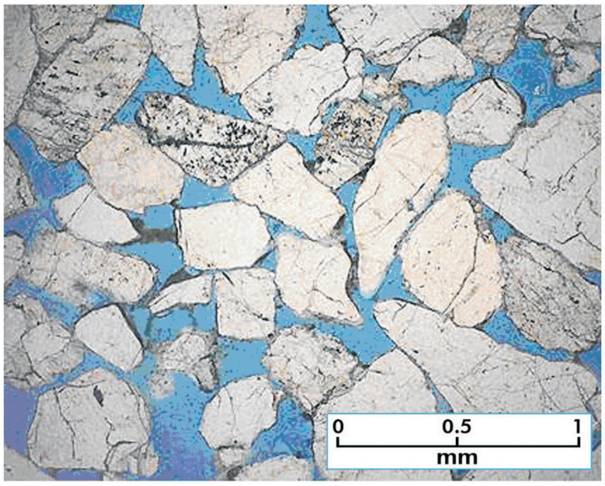
Several types of rock formations are suitable for CO_2 storage. These include depleted oil and gas reservoirs, deep saline formations and unmineable coal seams. Deep, porous rock formations with trapped natural fluids such as oil, natural gas or highly salty and unusable water are common throughout the world. Geologists have found that these formations have the capacity to securely hold vast amounts of CO_2, potentially equivalent to hundreds of years of man-made emissions.

The same geologic forces that kept the original fluids in place will also secure the CO_2. Once injected, the CO_2 will be trapped initially in tiny pores within the storage rocks. Over time, the CO_2 will dissolve in water already in the rock formation and then may combine chemically with the rocks to trap it even more securely. The CO_2 will be far below the surface, separated from usable groundwater by thick, impermeable barriers of dense rock.



CO_2 will be injected at depths below 0.8 km (2600 feet). CO_2 increases in density with depth and becomes a supercritical fluid below 0.8 km. Supercritical fluids take up much less space than gases, as shown in this figure, and diffuse better than either gases or ordinary liquids through the tiny pore spaces in storage rocks. The blue numbers in this figure show the volume of CO_2 at each depth compared to a volume of 100 at the surface.

Image Source: CO2CRC



CO_2 will be trapped as a supercritical fluid in tiny pore spaces in the storage rock, as is shown by the blue spaces between the white grains of quartz in this photograph of a microscopic section of storage sandstone.

Image Source: CO2CRC

Safe, long-term underground geologic storage (sequestration) of CO_2 must be conducted properly. This means thorough planning and geologic analysis of the storage site, safe operating practices, careful monitoring of the underground CO_2 during injection, and continued monitoring for some time afterward. Reliable geological surveys can prove the presence of impermeable rock barriers and the capability of deep rock formations to hold fluids. Geologic storage uses established techniques and equipment used over many years by industry, although more advanced technologies designed specifically for CO_2 injection are also being developed. Storage sites are monitored so that any undesirable CO_2 movement can be readily detected and fixed.

Geologic storage projects have already successfully stored millions of tons of CO_2, some for many years, without detectable leakage. For example, the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project in Canada has injected over 5 million tons of CO_2 into a depleted oil field. Extensive monitoring by an international team of scientists has detected no leakage. Similarly, the Sleipner Project off the coast of Norway has injected over 10 million tons of CO_2 in a deep saline formation with no leakage. Other projects are now underway and many new projects are planned throughout the world in the years to come.

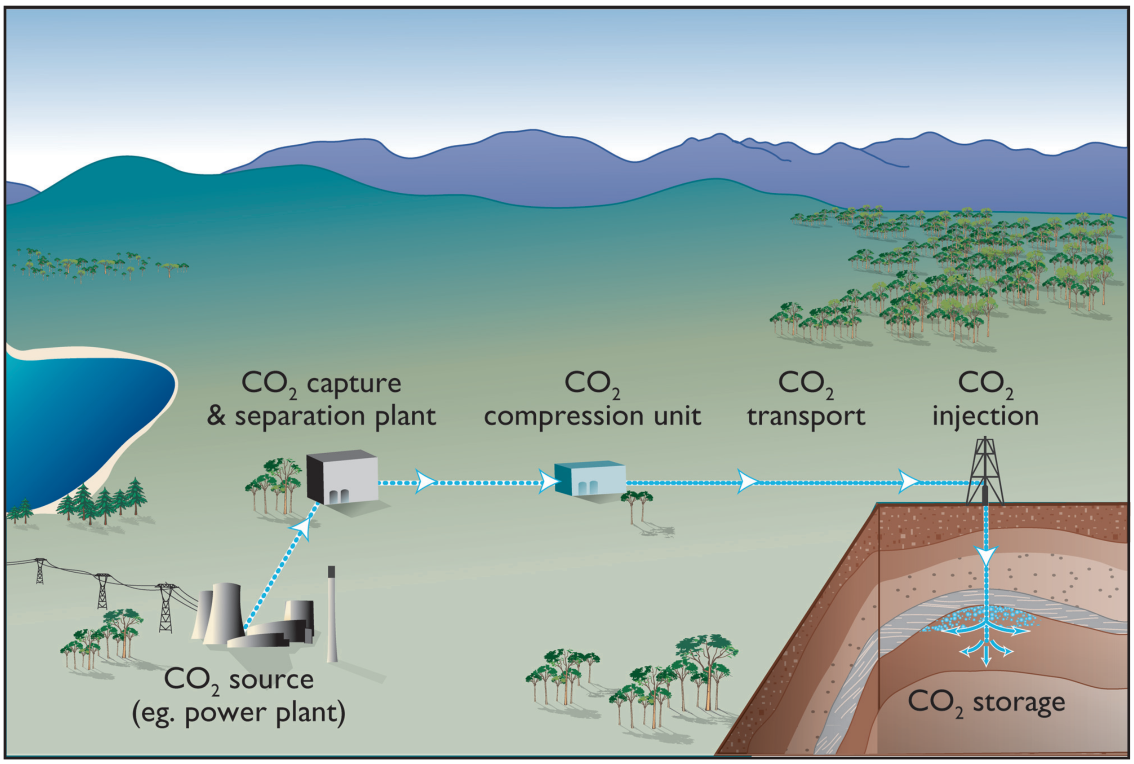
Geologic storage of CO_2 can be a vital part of the solution to the problem of global climate change. Methods and technologies are developing rapidly, as are the legal frameworks to regulate them. Geologic storage projects undertaken over the next ten years will be critical for demonstrating CO_2 storage in diverse geologic settings and will establish the basis for its widespread global application as a means of preventing climate change.

WHY STORE CARBON DIOXIDE UNDERGROUND?

Carbon Capture and Storage (CCS), also known as Carbon Capture and Sequestration, is the separation and capture of carbon dioxide (CO_2) from the atmospheric emissions of industrial processes and the transport and permanent disposal of the CO_2 in deep underground rock formations. By preventing CO_2 from large-scale industrial facilities from entering the atmosphere, CCS is a powerful tool for combating climate change. Geologic storage is the component of CCS in which the CO_2 is disposed of underground. Geologic storage is also sometimes called "geologic sequestration" or "geosequestration."

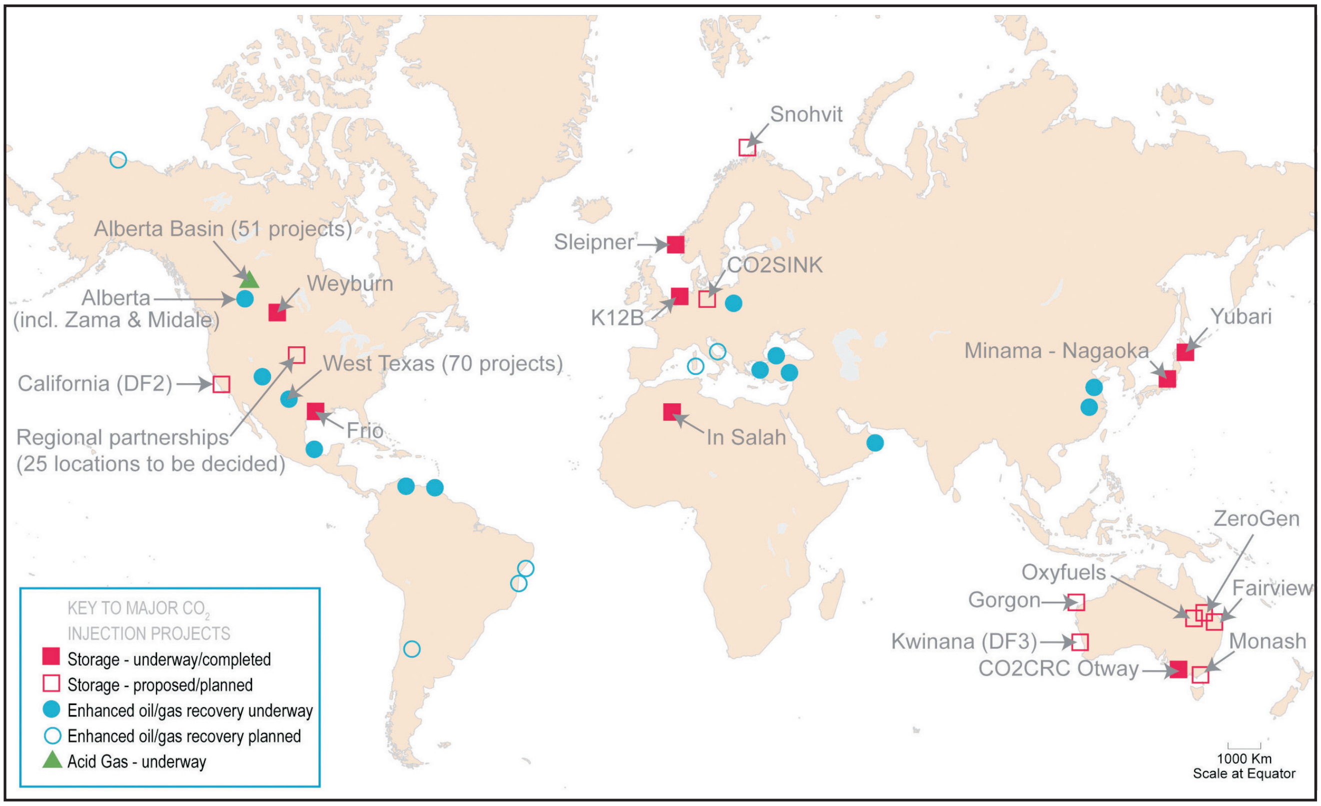
CO_2 from industry and other human activities is a major contributor to global climate change. The CO_2 for geologic storage comes from industrial facilities that emit large amounts of CO_2, particularly those that burn coal, oil or natural gas. These facilities include power plants, petroleum refineries, oil and gas production facilities, iron and steel mills, cement plants and various chemical plants. In CCS, CO_2 is not removed from the atmosphere. Rather, CO_2 that would otherwise have been emitted into the atmosphere is captured and disposed of underground.

CCS enables industry to continue with less disruption while minimizing industry's impact on climate change. Studies show that CCS could make a significant contribution to reducing CO_2 emissions. The greatest emissions reductions are achieved when all options for reducing CO_2 emissions are utilized, including energy efficiency, fuel switching, renewable energy sources and CCS.



Geologic storage is one component of Carbon Capture and Storage (CCS). In CCS, CO_2 is captured before it can be emitted into the atmosphere, transported to the injection site and then disposed of underground in suitable rock formations.

Image Source: CO2CRC



Geologic storage and related projects are in operation or proposed around the world to address climate change. Most are research, development or demonstration projects. Several are part of industrial facilities in commercial operation.

Image Source: CO2CRC

This booklet is a summary of what is currently known about the permanence and safety of geologic storage of CO_2. The information it contains is based on a number of different sources and the input of expert geologists who participated in its development. The most comprehensive source is Chapter 5: *Underground Geological Storage* of the Special Report on Carbon Dioxide Capture and Storage by the Intergovernmental Panel on Climate Change (IPCC).[1] The IPCC Special Report is available to be downloaded on the IPCC website at http://www.ipcc.ch.

This booklet describes:

- ✓ The properties of CO_2,
- ✓ Where the CO_2 can be stored,
- ✓ How geologic storage should be conducted,
- ✓ The permanence of underground disposal,
- ✓ The potential impacts of leakage, and
- ✓ How potential leaks could be detected and fixed.

1 IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

Since each geologic storage project is different, this booklet also provides a list of questions to ask project developers about permanence and safety. The answers should help decision makers and the public understand geologic storage.

This booklet makes no claims about specific projects. A thorough and accurate evaluation of specific projects requires substantial expertise in geology and geological engineering as well as detailed information on the proposed storage site.

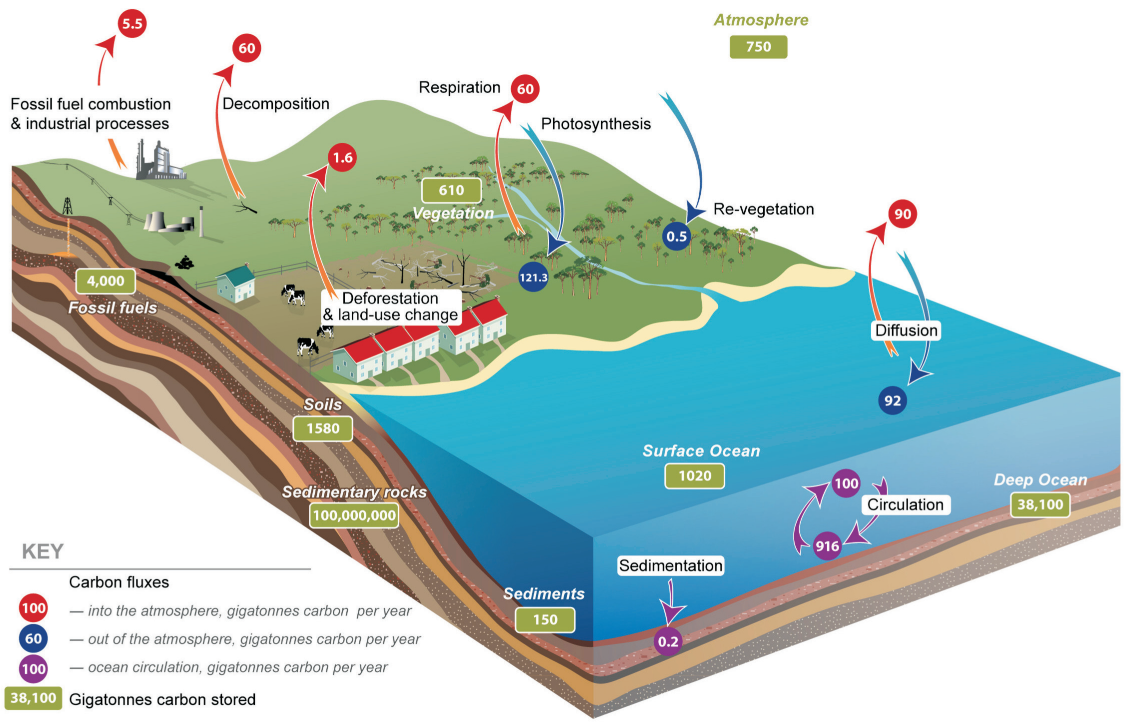
Geologic storage uses a set of rapidly-evolving technologies and practices. CO_2 has been injected into oil reservoirs to increase recovery of oil for over 30 years. Since the early 1990s, considerable research and development around the world has been devoted to geologic storage for the purpose of reducing CO_2 emissions. It is now employed for that purpose in some commercial projects. Geologic storage needs further development, however, before it can become widely commercial; researchers are learning more virtually every day.

WHAT IS CO_2?

CO_2 is a naturally-occurring substance made up of carbon and oxygen, two of the most common chemical elements on earth.

Under normal atmospheric conditions, CO_2 is a gas. It can be compressed into a liquid, frozen into a solid (dry ice) or dissolved in water (carbonated beverages, beer and sparkling wines). In the atmosphere, CO_2 comprises about 0.04 percent of the air we breathe. It also occurs naturally in both fresh and sea water and in the ground. Carbon dioxide is not flammable, does not explode and is not toxic. In fact, it is used in some fire extinguishers.

CO_2 is necessary for life on earth. People and animals inhale oxygen from the air and exhale CO_2. Meanwhile, green plants absorb CO_2 for photosynthesis and emit oxygen back into the atmosphere. CO_2 is also exchanged between the atmosphere and the oceans and is emitted or absorbed in other natural processes. Working together in a natural system called the carbon cycle, these processes have in the past kept the levels of CO_2 in the atmosphere stable over time.



Nature's carbon cycle normally keeps CO_2 levels in balance, but human activity, mostly the burning of fossil fuels, produces more CO_2 than nature can absorb. The arrows in this diagram show the annual flows of carbon in billion tonnes (metric tons). The human contribution is relatively small, but enough to throw the cycle off balance. The extra CO_2 stays in the atmosphere, where it causes global warming.

Image courtesy of CO2CRC, with values of carbon fluxes and sinks sourced from NASA Earth Science Enterprise and the International Energy Agency.

CO_2 is a greenhouse gas. That is, its presence in the atmosphere traps heat energy from the sun. This keeps the climate warm enough for life to continue. The balance is delicate, however. As atmospheric CO_2 levels increase from natural levels the climate becomes warmer, changing the natural balance in most parts of the world. This has a wide range of major disruptive impacts on the environment, natural resources and human communities throughout the world. Both the temperature and the impacts increase with rising CO_2 levels.

Living things consist largely of water and molecules containing carbon. When fuels derived from living things such as wood or fossil fuels (oil, coal or natural gas) are burned, the carbon combines with oxygen to form CO_2 that is released into the atmosphere. People have thrown the natural carbon cycle out of balance by burning fossil fuels. More CO_2 is now entering the atmosphere than can be naturally absorbed, contributing to global warming. Geologic storage returns carbon back into the ground where it was captured eons ago when the remains of prehistoric plants and animals decomposed into coal, oil and natural gas.

CO_2 also has many practical uses. For example, it is used in industries as varied as chemicals, metals, food and beverages, healthcare, pulp and paper, electronics and waste treatment. It is used to make fertilizer; it adds fizz to carbonated beverages; it is used in commercial freezing and refrigeration in its frozen form, dry ice. The amount of CO_2 needed for all these uses, however, is miniscule compared to the amount emitted into the atmosphere by burning fossil fuels.

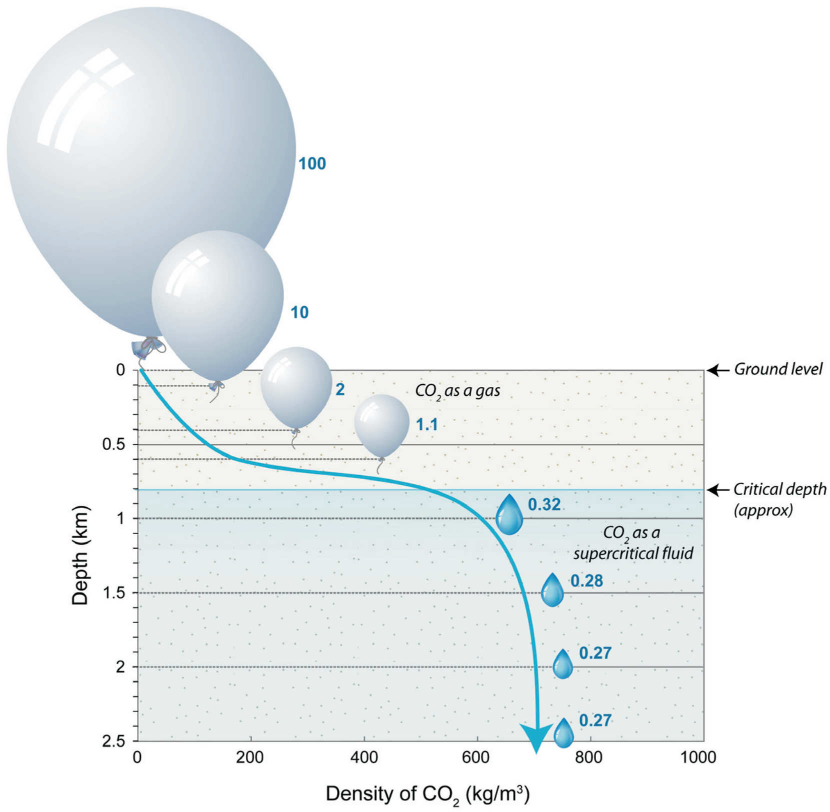
WHERE CAN THE CO_2 BE STORED?

In geologic storage, CO_2 is injected under high pressure into very deep underground rock formations. In many areas, these rocks already securely hold fluids such as oil, natural gas or water that is too salty to use. Several natural trapping mechanisms keep these natural fluids in place, often for millions of years. These trapping mechanisms can do the same for CO_2.

CO_2 itself has been securely trapped in rock formations in many places around the world. Geologists searching for CO_2 storage sites look for rock formations that already securely hold fluids and therefore have proven to have these trapping mechanisms.

Injection of CO_2 as a Supercritical Fluid

In geologic storage, CO_2 is injected under pressure into suitable subterranean geologic formations, taking advantage of natural trapping mechanisms in those formations. In fact, the CO_2 is injected at sufficiently high pressures and temperatures that it becomes what scientists call a *supercritical fluid*. Supercritical fluids are like gases in that they can diffuse readily through the pore spaces of solids but, like liquids, they take up much less space than gases. Supercritical CO_2 is sometimes used as a non-toxic method for decaffeinating coffee and dry cleaning clothes. Supercritical CO_2 compresses further as the depth increases, increasing the amount that can be stored in the same volume of rock. High pressure at sufficient depths (i.e., greater than 800 meters or 2600 feet) maintains the supercritical fluid state. Various trapping mechanisms can keep it at these depths.



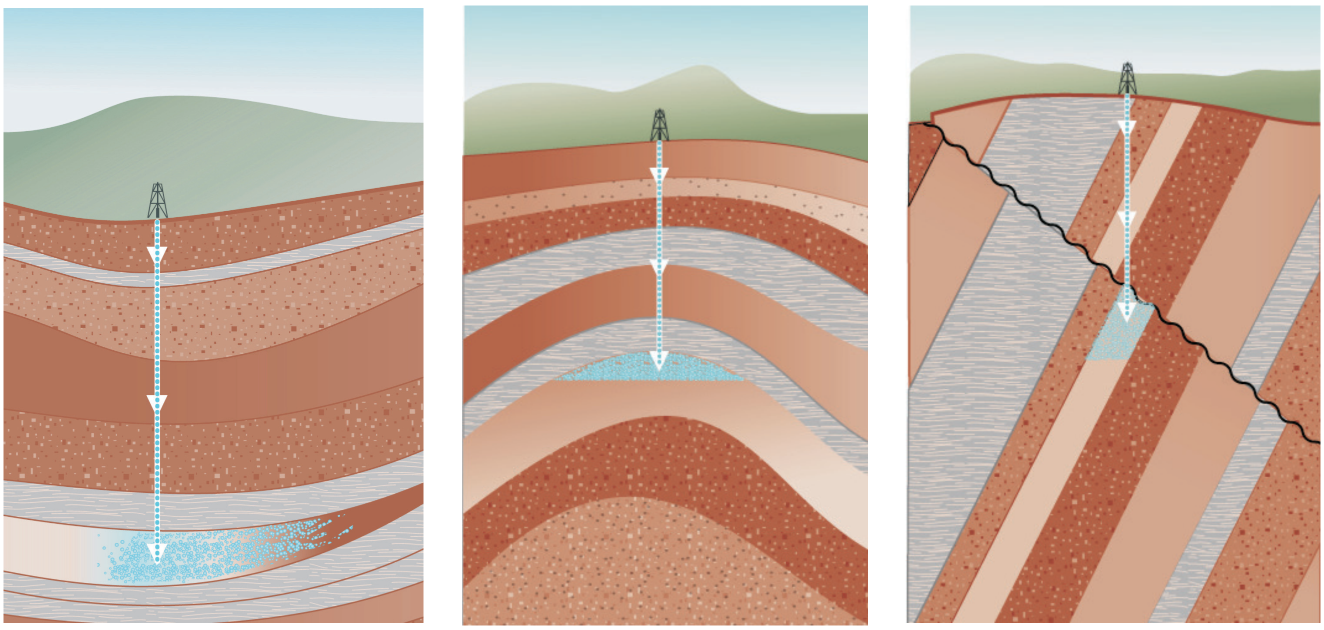
CO_2 will be injected at depths below 0.8 km (2600 feet). CO_2 increases in density with depth and becomes a supercritical fluid below 0.8 km. Supercritical fluids take up much less space, as shown in this figure, and diffuse better than either gases or ordinary liquids through the tiny pore spaces in storage rocks. The blue numbers in this figure show the volume of CO_2 at each depth compared to a volume of 100 at the surface.

Image Source: CO2CRC

Trapping Mechanisms

A trap is a configuration of rocks suitable for containing fluids and sealed by a relatively impermeable formation through which fluids will not migrate. CO_2 is held in place in a storage reservoir through one or more of five basic trapping mechanisms: stratigraphic, structural, residual, solubility, and mineral. Trapping mechanisms depend on the local geology and work together when more than one is present.

Generally, the initial dominant trapping mechanisms are stratigraphic trapping or structural trapping, or a combination of the two. *Cap rock* is a dense layer of impermeable rock that overlays the rocks holding the CO_2 and forms a continuous primary seal. In *stratigraphic trapping*, cap rock, sometimes coupled with impermeable rocks elsewhere within the same layer as the CO_2, forms a closed container to trap the CO_2. In *structural trapping*, impermeable rocks shifted by a fault or fold in the geologic strata hold the CO_2 in place. In addition, CO_2 storage rocks are generally separated from the surface by other thick layers of impermeable rock, called secondary seals.



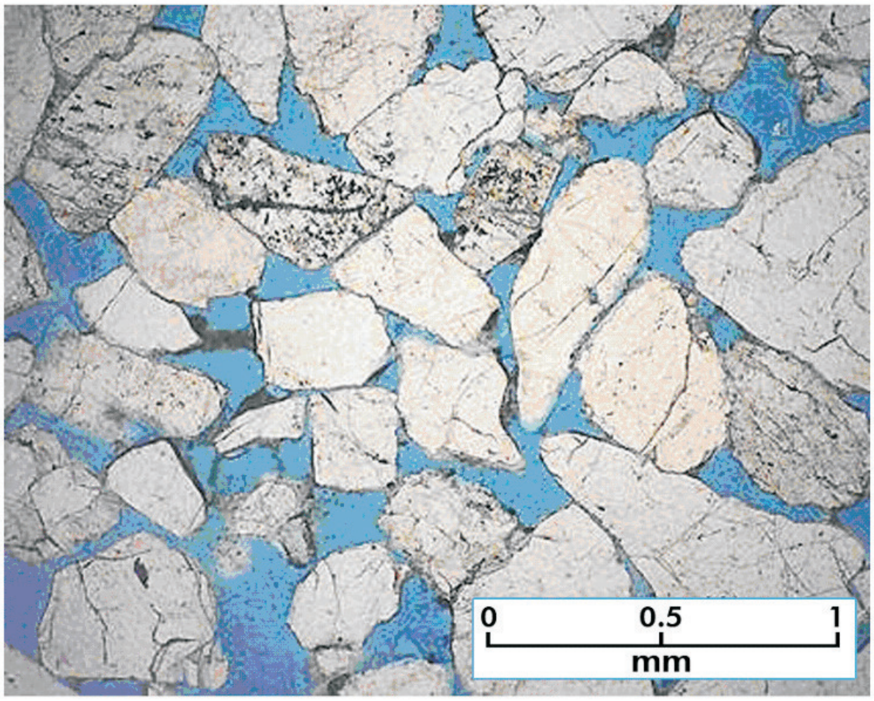
In stratigraphic trapping (left), CO_2 is trapped by an overlying layer of cap rock coupled with impermeable rock within a narrowing of the storage formation. In structural trapping, CO_2 is trapped by a fold in the rock formations (middle) or by impermeable rock layers shifted along a sealing fault (right) to contain the CO_2. These are just three of several possible ways that stratigraphic and structural trapping could contain CO_2.

Image Source: CO2CRC

Over time, other even more secure trapping mechanisms take over. In *residual trapping*, which usually begins after injection stops, the CO_2 is trapped in the tiny pores in rocks by the capillary pressure of water. After injection stops, water from the surrounding rocks begins to move back into the pore spaces containing the CO_2. As this happens, the CO_2 becomes immobilized by the pressure of the added water.

As more CO_2 is injected, the CO_2 moves further from the injection site and, since it is lighter than the highly saline water or oil, the CO_2 may also initially rise toward the top of the porous storage rocks, where stratigraphic and structural trapping keep it in place. Injection pressures must be high enough to force the liquid CO_2 into the porous rock, but not so high as to break the cap rock forming the primary seal immediately above the storage formation.

Much of the injected CO_2 will eventually dissolve in the saline water or in the oil that remains in the rock, somewhat like sugar dissolves in water to make sweetened beverages. This process, which further traps the CO_2, is *solubility (or dissolution) trapping*. Solubility trapping forms a denser fluid which may then sink to the bottom of the storage formation. Depending on the rock formation, the dissolved CO_2 may react chemically with the surrounding rocks to form stable minerals. Known as *mineral trapping*, this provides the most secure form of storage for the CO_2, but it is a slow process and may take place over thousands of years. Currently, research is underway to evaluate how mineral trapping works and the long-term impact of CO_2 on fluids and rocks in a variety of geologic settings.



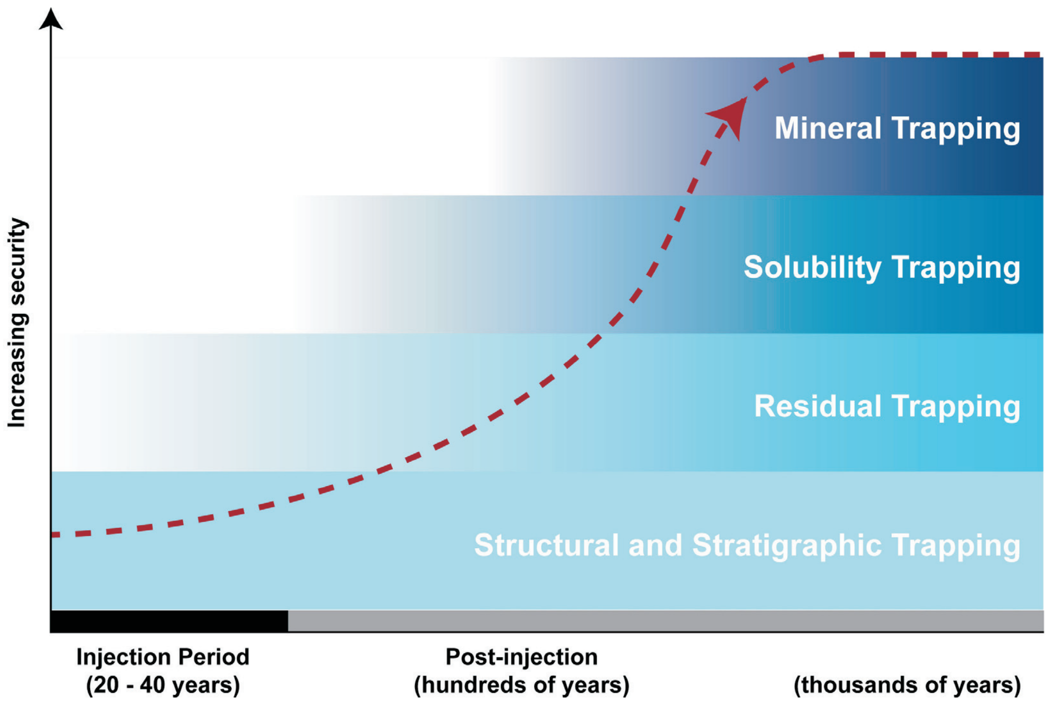
CO_2 will be trapped as a supercritical fluid in tiny pore spaces within the storage rock, as is shown by the blue spaces in this photograph of a microscopic section of storage sandstone. The white grains are mostly quartz.

Image Source: CO2CRC

Evaluation of the properties of rocks that may be used for storage or seals can be complex. Two important attributes of the rocks are visible in the above picture. *Porosity* is a measure of the space in the rock for storing fluids. *Permeability* is a measure of the ability of the rock to allow fluid flow. Permeability is strongly affected by the shape, size and connectedness of the spaces in the rock.

Rocks suitable for storage typically (but with some exceptions) have high porosity to provide space for the CO_2 and high permeability for the CO_2 to move into that space. By contrast, the seals covering the storage formation typically have low porosity and permeability to trap the fluids stored below. Another property of the potential storage site called *injectivity* is also important. Injectivity is the rate at which the CO_2 can be injected into a storage reservoir formation. Typically, the CO_2 must be injected at much the same rate as it is captured from the sources. The trade-offs between the injectivity required, the reservoir storage capacity, and the quality of the seal can be intricate and require careful evaluation by geologists and geological engineers.

These trapping processes take place over many years at different rates. Generally, the longer CO_2 stays underground, the more secure its storage becomes. With the passage of time, more-secure trapping mechanisms are increasingly likely to have significant effect. Which trapping mechanisms apply and the rates at which they work can vary widely with the geology. Scientists are now developing the tools to accurately predict how these mechanisms will work over time in a diverse set of specific geological settings.



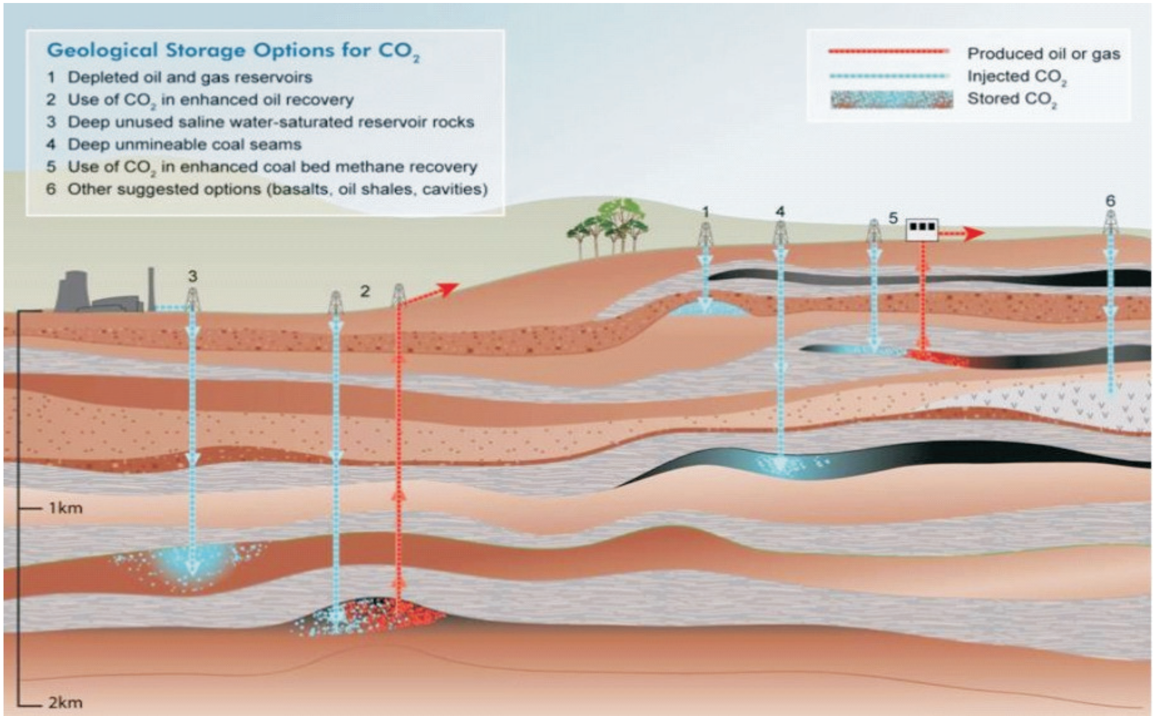
As time goes on, increasingly secure trapping mechanisms come into play and the overall security of storage increases.

Types of Underground Storage Sites for CO_2

Candidate sites for geologic storage include depleted oil and gas fields, deep saline formations and deep unmineable coal seams. Both depleted oil and gas fields and deep saline formations use the five trapping mechanisms described above. Such geological formations have cap rocks on top of the porous sedimentary rocks that could contain CO_2. Deep unmineable coal seams are also potential candidates for geologic storage, but use a somewhat different trapping mechanism involving the CO_2 fixing on or in the coal particles. Much of the vital work on geologic storage over the next 10 years will involve demonstrating storage in diverse geological settings so that it can be deployed afterward on a widespread global basis.

In depleted oil and gas fields, CO_2 fills the pores in the rock that were once filled with oil or natural gas. Depleted oil and gas fields are likely to be used early for CO_2 storage because, in some cases, the injected CO_2 could lead to greater production of oil or natural gas. This practice is known as Enhanced Oil Recovery (EOR) or Enhanced Gas Recovery (EGR). EOR with injected CO_2 is a common practice today in some oil fields, having been used for over 30 years. Increased production of oil or gas could offset the costs of capture and storage. In other cases, the CO_2 may be injected into the pores of rocks where the oil or gas has already been produced, resulting in no further oil or gas production.

Natural trapping mechanisms in oil and gas reservoirs have successfully contained oil, gas and water for millions of years. The geology of most oil and gas fields has been thoroughly studied. In addition, the oil and gas industry widely uses accurate computer models of the underground behavior of these fluids. Such models are being adapted to CO_2. One concern in some oil and gas fields is the impact of any abandoned oil and gas production wells since improperly sealed wells may provide an escape route for CO_2. Addressing this concern requires analyzing prior drilling activity in the area and ensuring that closed wells are properly sealed.



Several types of rock formations are suitable for CO_2 storage, including depleted oil and gas fields, deep saline formations and deep, unmineable coal seams. Other types of formations such as basalts and oil shales are being examined by scientists for possible future use.

Image Source: CO2CRC

Deep saline formations are very deep, porous rocks containing water that is unusable because of its high salt or mineral content. Such formations are widely dispersed throughout the world, including in areas with no appreciable oil and gas production. These formations meet all the necessary criteria to provide long-term storage. Injected CO_2 adds to fluid already trapped in the rocks, eventually dissolves in the saline water, and may combine chemically with the surrounding rocks. Deep saline formations contain most of the global geologic storage capacity for CO_2 and are likely to become the most widely used type of geologic storage site.

<u>Deep, unmineable coal seams</u> are also possible storage sites. CO_2 can enter into very small spaces, called micropores, within the coal. Generally, CO_2 that enters coal in that way is held so tightly that it will remain in place even without cap rocks. Coal often contains methane. In these micropores, CO_2 can, in some cases, displace the methane which can be recovered and used as a fuel. This type of methane production is called *Enhanced Coal Bed Methane.* It is experimental at this time as greater knowledge is needed on the fundamental processes of CO_2 uptake and methane release from coal.

<u>Basalt and oil shale formations</u> are also possibilities, but their potential for storing CO_2 is currently theoretical.

Disposal of Other Substances with the CO_2

In most cases, small amounts of other substances accompanying CO_2 will also be disposed of underground. Although emissions controls and CO_2 separation can be highly efficient, they are not 100 percent effective and some other substances may be present in the captured CO_2 stream. The types and amounts of those substances will depend on the process from which the CO_2 is captured.

The other injected substances may include gases from the air such as nitrogen and oxygen, small amounts of pollutants not removed by any emissions controls such as sulfur oxides, nitrogen oxides and particulate matter, or hydrocarbons or other gases such as hydrogen sulfide. Re-injecting a mixture of CO_2 and hydrogen sulfide byproducts of oil and gas production (known as "acid gas") into depleted oil reservoirs, for example, has long been an accepted means of pollution control since the 1990s in Alberta, Canada and is now being planned for Enhanced Oil Recovery. To the extent that the other injected substances are air or water pollutants, underground disposal further reduces those forms of pollution. The impact of the other substances on CO_2 storage capacity, however, needs to be understood prior to disposal.

Capacity for CO_2 Storage

It is now clear that rock formations appropriate for geologic storage exist throughout the world and that they have a vast capacity compared to the need. Geologists only recently began estimating capacity for geologic storage and new discoveries are still being made. In its Special Report on Carbon Dioxide Capture and Storage, the Intergovernmental Panel on Climate Change estimated total global CO_2 storage capacity to be in a range that is hundreds of times annual CO_2 emissions from large industrial sources. That report also noted that, since CO_2 storage is so new, current methods for estimating storage capacity require more development and many gaps exist in capacity estimates at the global, regional and local levels. This means that global storage capacity may be even greater than estimated in that report.

HOW WILL CO_2 STORAGE BE CONDUCTED?

Geologic storage projects are generally conducted in three sequential phases: planning and construction, injection, and post injection. While the specifics of each project differ, similar activities are involved in each phase. The activities in each of these phases can affect the permanence and safety of the underground storage.

Planning and Construction

Planning starts with an industrial facility capable of capturing the CO_2. The amount of CO_2 that is to be captured is projected and a search begins for a geologic formation to store the projected amount of CO_2. In the future, large sources of CO_2 such as coal-fired power plants may be purposely located near geologic formations suitable for geologic storage. A suitable storage site must have a number of characteristics. See box below.

What is a Good Geologic Storage Site?

Accessibility

- ✓ The location is economically accessible to the source of CO_2.
- ✓ The organization conducting storage has all the legal rights to do so on that site.

Capacity

- ✓ Storage formation has adequate porosity and permeability to store CO_2.
- ✓ The storage formation has adequate total storage volume to serve the intended sources.

Injectivity

- ✓ The formation can store CO_2 at the rate required to serve the intended sources.

Storage Security

- ✓ Well-defined trapping mechanisms exist within the storage formation.
- ✓ The CO_2 will be stored deep enough to be supercritical.
- ✓ Cap rock is adequately impermeable, continuous and thick to prevent upward migration.
- ✓ The geologic environment is adequately stable to ensure the integrity of the storage site.
- ✓ No pathway faults or uncapped wells penetrate the cap rock and storage formation.

If the CO_2 injection site is not at the same place as the source, CO_2 must be liquefied and transported by pipeline or ship. Pipeline transportation of CO_2 is a well-established and safe practice. About 3000 miles (4800 km) of CO_2 pipelines exist in the United States alone. In one commercial project, a 200 mile (320 km) pipeline carries CO_2 captured at a coal gasification plant in the U.S. state of North Dakota to a geologic storage site in the Canadian province of Saskatchewan. Ships to transport CO_2 over water are currently being designed.

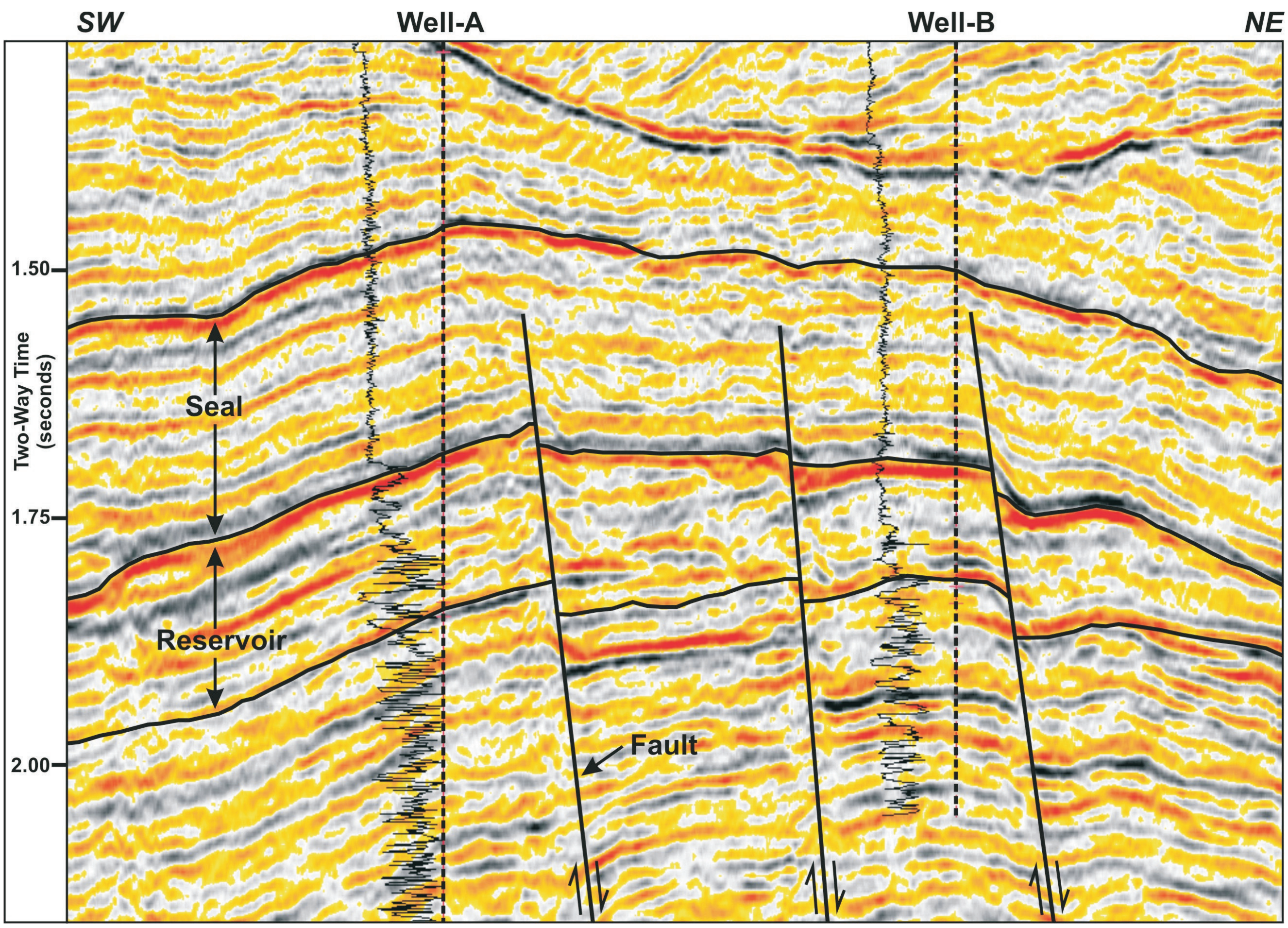
Two types of analyses are typically conducted during planning:

1. Site identification and selection finds possible alternative storage locations and pipeline routes. The most appropriate storage reservoir and the locations for facilities such as pipelines, injection wells and monitoring wells are then selected on the basis of technical, cost and regulatory considerations.

2. <u>Site characterization</u> studies the geology of a prospective storage reservoir and surrounding rock formations. Good site characterization is essential to ensure effective and permanent storage for the anticipated quantities of CO_2.

Site characterization typically starts with descriptions of geological structures, groundwater and rock chemistry. Ultimately, it should address what will happen to the injected CO_2. Most of the analysis focuses on the storage reservoir and the cap rock immediately above the reservoir that will be the primary seal, but rock formations above the cap rocks also need to be understood to determine whether they may be secondary seals. Analyses may include simulations and modeling of the behavior of the injected CO_2 over time and field tests to verify the simulations. Similar simulations and modeling have been used for many years for oil and gas production. The behavior of injected CO_2 is somewhat different and work is currently underway to refine simulation and modeling methods for this application.

The detail and depth of the planning analyses will vary with specific needs. These studies require geologic data that may be collected by seismic surveys and by drilling. Some of this data may be available from prior geologic work such as government surveys or oil and gas exploration. In many other places, new data will have to be collected.



Seismic imaging uses reflected sound waves to create pictures of underground rock formations. Pictures such as this show potential CO_2 reservoirs and seal rocks as well as other geologic features such as faults. After injection begins, these pictures can show the location of the CO_2. This picture also shows where two test wells were drilled to make measurements and take rock samples. Taken together, all this information can provide an accurate and detailed understanding of conditions underground.

Image Source: CO2CRC

Rock samples are taken by drilling into potential storage sites. These samples show the types of rocks in the formations identified by seismic imaging and they enable the properties of those rocks that affect storage to be evaluated.

Image Source: CO2CRC

Following these studies, detailed plans for the project are developed. These plans typically lay out how the facility will operate under normal conditions and possible contingency responses. Risk assessments will typically also be performed. In the oil and gas industry, risk assessments for similar injection operations are routine and are conducted with a high degree of confidence based on extensive experience. Work is currently underway to develop risk assessment methodologies specifically for geologic storage.

If studies produce acceptable results, the necessary rights, permits and licenses are obtained. Finally, as plans and permits allow, injection wells are drilled and connected with the CO_2 pipeline. In some cases, separate wells for monitoring CO_2 in the storage formation may also be drilled. If the storage site is located offshore, then offshore platforms or subsea installations will be used.

Injection and Post Injection

Once operations start, CO_2 is compressed into a supercritical fluid and pumped under high pressure into the storage formation. The equipment and practices for injection are already widely used in the oil and gas industry. Injection equipment is fully commercial, although more advanced technologies for CO_2 injection are also being developed.

Industry practice for the injection of fluids into geologic formations is well established and regulated in many areas. Indeed, CO_2 is safer to handle than the oil and gas routinely handled in similar well operations because it is not flammable, explosive or toxic. Since CO_2 is colorless and odorless, however, instrumentation is required to detect it. Industry already has substantial experience handling it and using such instrumentation. For example, CO_2 is routinely injected into some oil fields to increase the oil production through EOR.

During the period when injection is taking place, Measurement, Monitoring and Verification (MMV) activities are conducted to ensure that the correct amount of CO_2 is injected, that it is injected effectively and safely, and that no unwanted migration occurs. Data is compared to similar information gathered in a baseline survey prior to the beginning of injection. Further computer modeling can also be conducted during this time based on actual measurements to refine the projections of CO_2 behavior made during the planning activities. If any unwanted migration is identified, the leaks can be stopped, as is explained in a later section. Some MMV activities usually will continue for some time after injection has ended to ensure that no later unwanted migration takes place.

CO_2 injection wells are generally small and have little impact on surrounding areas, as shown in this picture of a CO_2 injection well in Canada.

Image Source: IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project, Final Phase.

WILL THE CO_2 STAY UNDERGROUND?

Geologic storage sites should be selected for their ability to trap CO_2 underground over a very long time, making leakage very unlikely. Geologic storage builds on an extensive base of experience successfully injecting fluids underground, including CO_2. In addition, naturally-occurring underground concentrations of gases, including CO_2 and natural gas, have remained underground for millions of years.

Potential for Leakage from Storage

Studies of geologic storage test sites suggest leakage rates of less than 1 percent over thousands of years. Best estimates of leakage rates by geologists are well below levels that would cause any significant increase in atmospheric CO_2 or risk to public safety.

Most geologic storage projects are expected to take advantage of multiple trapping mechanisms. As a result of a combination of stratigraphic, structural, residual, solubility and mineral trapping, any CO_2 movement out of the formations is unlikely. Evidence shows that these kinds of movements are very slow for appropriately selected and designed sites that are operated and monitored properly. Moreover, the CO_2 will typically be stored in rock formations that have proven their ability to retain fluids, some for millions of years. Injected CO_2 would not exist as an underground gas bubble that could rapidly burst forth to the surface.

The greatest risk for escape of CO_2 may come from other wells, typically for oil and gas, which penetrate the storage formation. Such wells need to be properly sealed in order to ensure that they do not provide pathways for the CO_2 to escape into the atmosphere. Research is currently underway to better determine the effect of CO_2 on materials such as cement used to seal such wells. Planning for geologic storage must take such wells into account. This may be an issue in areas with many older abandoned wells that may be poorly documented. Nonetheless, such leaks appear to be very rare in West Texas, which has many of these older, undocumented wells, and where CO_2 has been widely injected for EOR since the 1970s. CO_2 escaping through water wells is much more unlikely since water wells are usually much shallower than the storage formation.

Relevant Industrial Experience

The oil industry has extensive experience successfully injecting CO_2 underground to increase oil production through Enhanced Oil Recovery. Similarly, an experimental project injected CO_2 to displace natural gas and enhance its production from a formation in the Netherlands and this may soon be done elsewhere, as well.

Fluids have been injected without problems into deep geologic formations over many years for natural gas storage and disposal of waste products. Natural gas, acid gas, and various hazardous wastes are routinely injected underground. As a result, there is already significant experience for evaluating fluids injected deep underground. Underground injection has been used for short-term storage of natural gas for nearly 100 years. The majority of such projects, like proposed geologic storage projects, are in depleted oil and gas reservoirs or saline formations. The success of these projects has depended on the same factors needed for a successful CO_2 geologic storage site, for example, capacity, injectivity, and factors that affect storage security such as cap rock integrity, geological structure and composition of the rocks within the site. Acid gas—a mixture of hydrogen sulfide and CO_2—has been disposed of by injecting it into over 50 sites in western Canada since 1990.

Slow Downward Migration of CO_2 to Bottom of a Saline Formation

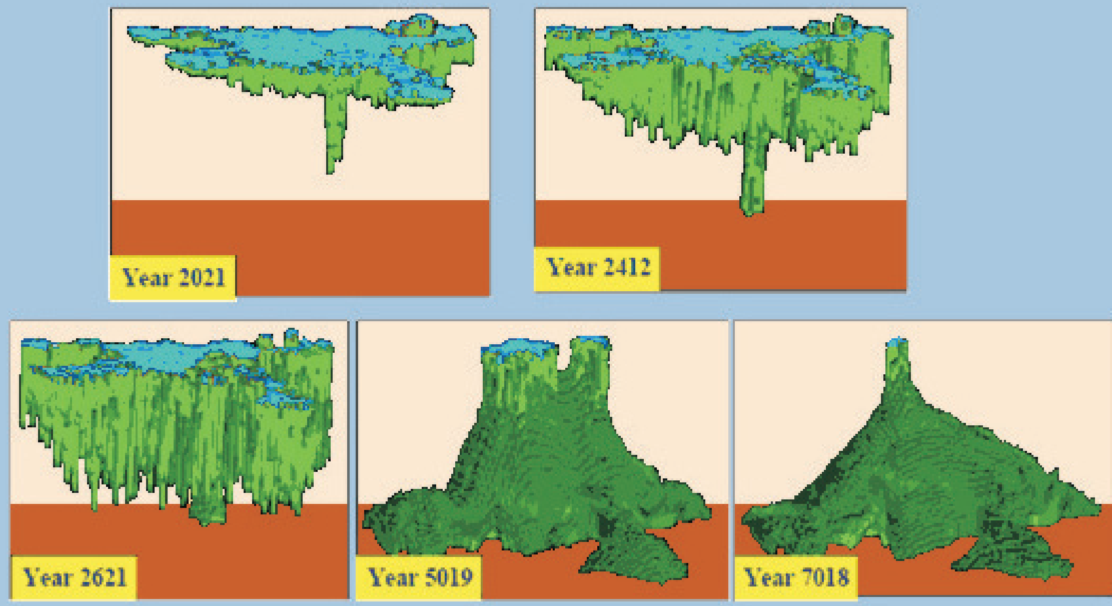


Image Source: Based on Gemini No. 1, 2004 (NTNU and Sintef) by permission.

The underground movement of CO_2 can be projected with computer simulations once enough data is gathered about a storage site. These figures project what will happen to the CO_2 in a current commercial CCS project. In the Sleipner project, 1 million tonnes (metric tons) of CO_2 per year has been injected into the deep Utsira saline formation off the coast of Norway since 1996. This formation contains extremely salty water known as brine.

Initially, the CO_2 will coalesce undissolved in the rock pores at the top of the saline formation beneath the thick seal of the cap rock. The blue shows undissolved CO_2. It will then dissolve and diffuse into the underlying brine. This CO_2-enriched brine, shown in green, is denser than the brine without the CO_2 and it will sink as the CO_2 dissolves. Over a long period of time—thousands of years—most of the CO_2 will be dissolved near the bottom of the brine formation.

These projections are consistent with actual measurements of the CO_2 injected at Sleipner so far. This is typical behavior for CO_2 in a saline formation, but results vary based on geologic trapping mechanisms of formations.

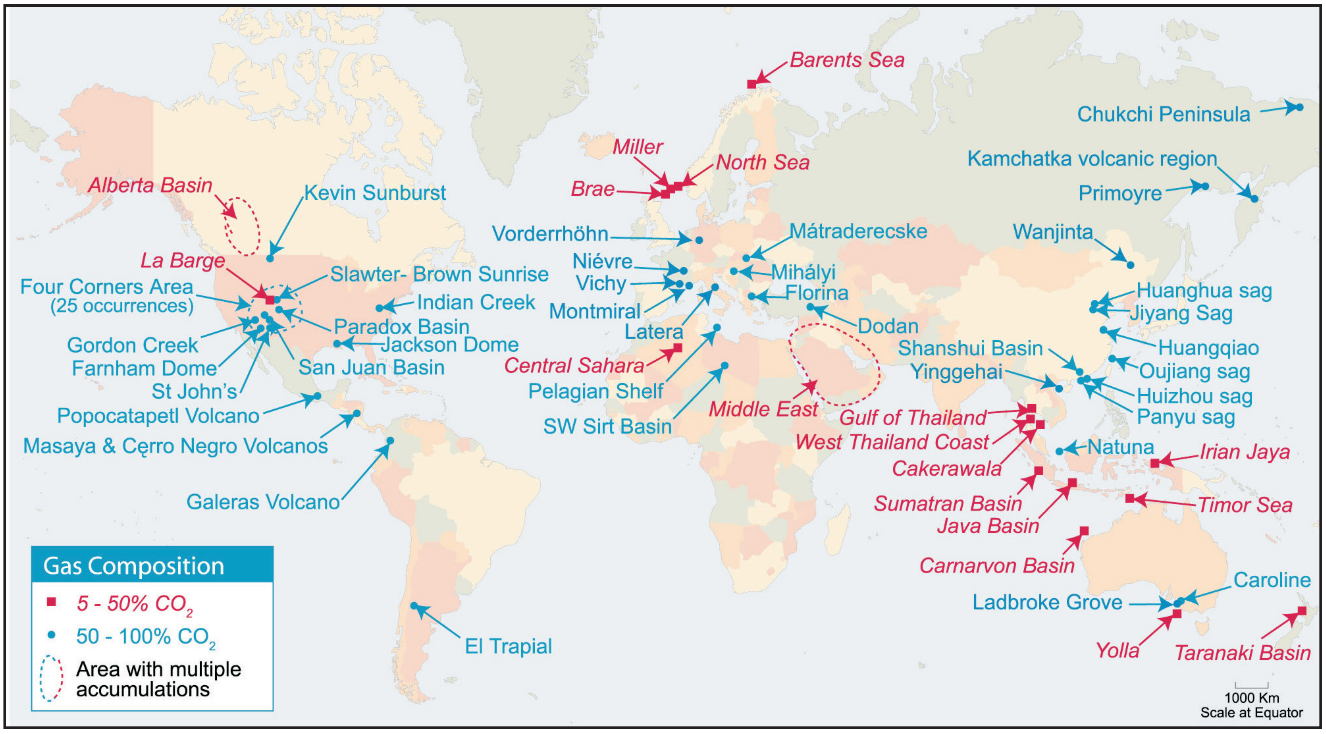
While they may share some technology and practices, the differences between natural gas storage and geologic storage of CO_2 are also significant. Natural gas is flammable and, under certain circumstances, explosive; CO_2 is neither flammable nor explosive. Natural gas is stored underground so that it can be easily re-extracted. By contrast, the CO_2 for a geologic storage project would be injected so that it would be difficult to extract. That is, as described earlier, the CO_2 would be injected as a supercritical fluid into a formation with strong trapping mechanisms, often much deeper than natural gas storage.

Geologic storage projects, while relatively recent, have already successfully stored millions of tons of CO_2 without detectable leakage, some for many years. For example, the Sleipner Project off the coast of Norway has injected over 10 million tons of CO_2 in a deep saline formation with no leakage. Similarly, the IEA GHG Weyburn-Midale CO_2 Storage and Monitoring Project in Canada has injected over 5 million tons of CO_2 into a depleted oil field. Extensive monitoring by an international team of scientists has detected no leakage. Other projects are now underway (see map, page 2) and many new projects are planned throughout the world in the years to come.

Regulatory standards for the safe transportation and injection of CO_2 are vital. Some environmental regulatory agencies have developed standards for siting, operation and abandonment of facilities for injecting CO_2 and others are developing such standards. Existing regulations for injection of other substances can be modified to apply to CO_2 injection. One aspect of these regulations is that equipment such as pipelines, valves and injection equipment must be resistant to the corrosive action of CO_2. In the United States, most underground injection activities are regulated by the U.S. Environmental Protection Agency (EPA), which sets minimum standards and regulatory requirements for underground injection activities. The EPA's goal is to protect drinking water. Any project that seeks to inject hazardous waste, for example, must submit a petition to the EPA demonstrating that injected fluid will not migrate from the disposal site for 10,000 years or more. EPA is now studying how these regulations could be modified for geologic storage of CO_2. In Canada, most drilling activities are regulated by provincial authorities. The province of Alberta has detailed regulations relating to the construction, operation and abandonment of five different classes of injection wells, including acid gas. In Australia, the government is modifying laws designed to regulated offshore oil and gas production to cover exploration for CO_2 injection and storage.

Natural Underground CO_2 Accumulations

The permanence of CO_2 storage depends on trapping mechanisms to keep the CO_2 in place. CO_2 exists naturally underground in many places throughout the world, either by itself, mixed with natural gas or oil or dissolved in water. Many geological formations have securely contained CO_2 without leakage over tens of millions of years. In other areas CO_2 naturally vents to the surface. Such areas are often the sites of natural spas and the sources of naturally sparkling mineral waters.



CO_2 is naturally trapped in many rock formations around the world. Scientists are studying these formations to understand how CO_2 behaves underground and design better geologic storage projects.

Image Source: Copyrighted material, Intergovernmental Panel on Climate Change, Special Report on Carbon Dioxide Capture and Storage, 2005, (used by permission).

Volcanoes and Geologic Storage - Not the Same

In volcanically active areas, underground CO_2 is released naturally when seals are inadequate. Most releases are harmless and difficult even to detect; others can be destructive. Lake Nyos in the African nation of Cameroon, for example, is located in a volcanic crater. Hot magma lies under the lake and vents CO_2 that accumulates in the lake. In 1986, there was a large-scale release of this naturally-occurring CO_2 that resulted in the deaths of some 1700 people. Since then, equipment has been installed in the lake to vent carbon dioxide slowly into the atmosphere and avoid any further accumulations. Similarly, releases of CO_2 from volcanic activity around Mammoth Mountain in California destroyed 40 hectares (99 acres) of pine trees, but did not harm people. In early 2006, however, three people were killed when they fell into a volcanic vent hidden by snowfall that contained CO_2 and other gases. Geologic storage sites will not have such vents.

Volcanic areas are generally well known and geologic storage sites should be chosen to avoid active volcanic areas. Volcanic systems typically vent many gases, including CO_2, and contain natural faults that provide pathways for gases to migrate to the surface at much higher rates than other areas. CO_2 releases in volcanically active areas are not representative of much slower movements through wells or small fractures that might be anticipated for geologic storage.

What about Earthquakes?

Storage sites are selected because they are inherently stable, have effective seals, and are located away from areas of seismic instability. Criteria for considering seismic effects in site selection are being developed.

CCS projects will likely be sited away from earthquake faults, but even earthquakes appear unlikely to cause leaks. Seals in a properly-designed project are very effective and most of the energy of earthquakes tends to spread at depths much shallower than where CO_2 would be stored. In October 2004, a major earthquake measuring 6.8 on the Richter scale occurred 20 kilometers from the injection site of a CO_2 geologic storage site at Nagaoka, Japan. This project stored CO_2 in a saline formation 1100 meters deep. Injection activities were halted immediately after the earthquake, but were resumed shortly thereafter. The storage formation was monitored before, during and after the earthquake and no leakage has ever been detected. Further evidence that earthquakes would not cause leaks is that a large number of producing oil and gas fields in California are near seismically active faults. They have much the same trapping mechanisms as CCS and earthquakes over many years have not caused them to leak.

Another consideration, known as induced seismicity, must be addressed in planning for CO_2 storage. Fluid injection in some geologic formations can cause fracturing and movement along faults. This may induce low levels of seismic activity, generally termed microseismic events. This was first noticed in the early 1960s in underground natural gas storage facilities. Since then, most natural gas storage facilities have been sited away from potentially active faults. This precaution nearly eliminated microseismic events. Seismic surveys can readily detect faults before a site is selected. Similar precautions can be used for CO_2 storage. Even where faults do exist, controlling injection pressures generally prevents induced seismicity. Most importantly, the well-established and long-standing practice of injecting CO_2 for EOR has not caused any significant seismic events.

WHAT IMPACTS COULD STORAGE HAVE?

CO_2 should be stored securely at depths far below the surface and usable groundwater. Significant impacts on the climate, to plants and animals or to groundwater are highly unlikely.

Will Leakage Affect the Climate?

The purpose of geological storage is to keep CO_2 out of the atmosphere where it affects the climate. The major impact of geologic storage will be a reduction in the CO_2 emissions that cause climate change. It is possible over time, however, that some CO_2 injected into geologic formations could escape into the atmosphere. In order for geologic storage to be effective for its intended purpose, the rate at which CO_2 escapes does not have to be zero, but it does have to be small enough to have no appreciable effect on atmospheric CO_2 concentrations.

The IPCC Special Report on Carbon Dioxide Capture and Storage estimated that it is likely that 99 percent or more of the CO_2 injected in appropriately selected and managed geological reservoirs would remain in the intended storage formation for at least 1000 years. The amount of CO_2 likely to enter the atmosphere is thus well below any level that would significantly impact the climate. Even if a few projects were to leak, the leaks are likely to be minimal and their total impact would be very small. The IPCC Special Report reached these conclusions based on substantial evidence from current CO_2 injection projects, other types of gas injection projects, and similar natural occurrences of CO_2 and natural gas in underground formations. As further experience is gained with geologic storage of CO_2, it will become possible to make more precise estimates of the probability and magnitude of leakages across a large number of storage sites.

Will Plants and Animals be Affected?

In normal atmospheric concentrations, CO_2 is harmless, but at much higher concentrations, it could affect plants and animals. CO_2 is odorless and is heavier than air, so it may tend to accumulate in low-lying areas. Plants could be affected by increased concentrations of CO_2 in the soil. Normally, CO_2 comprises 0.2 to 4.0 percent of the gases naturally found in soil. Concentrations of CO_2 above 5 percent of soil gas can be harmful to plant growth; extreme concentrations in the soil above 20 percent may kill plants.

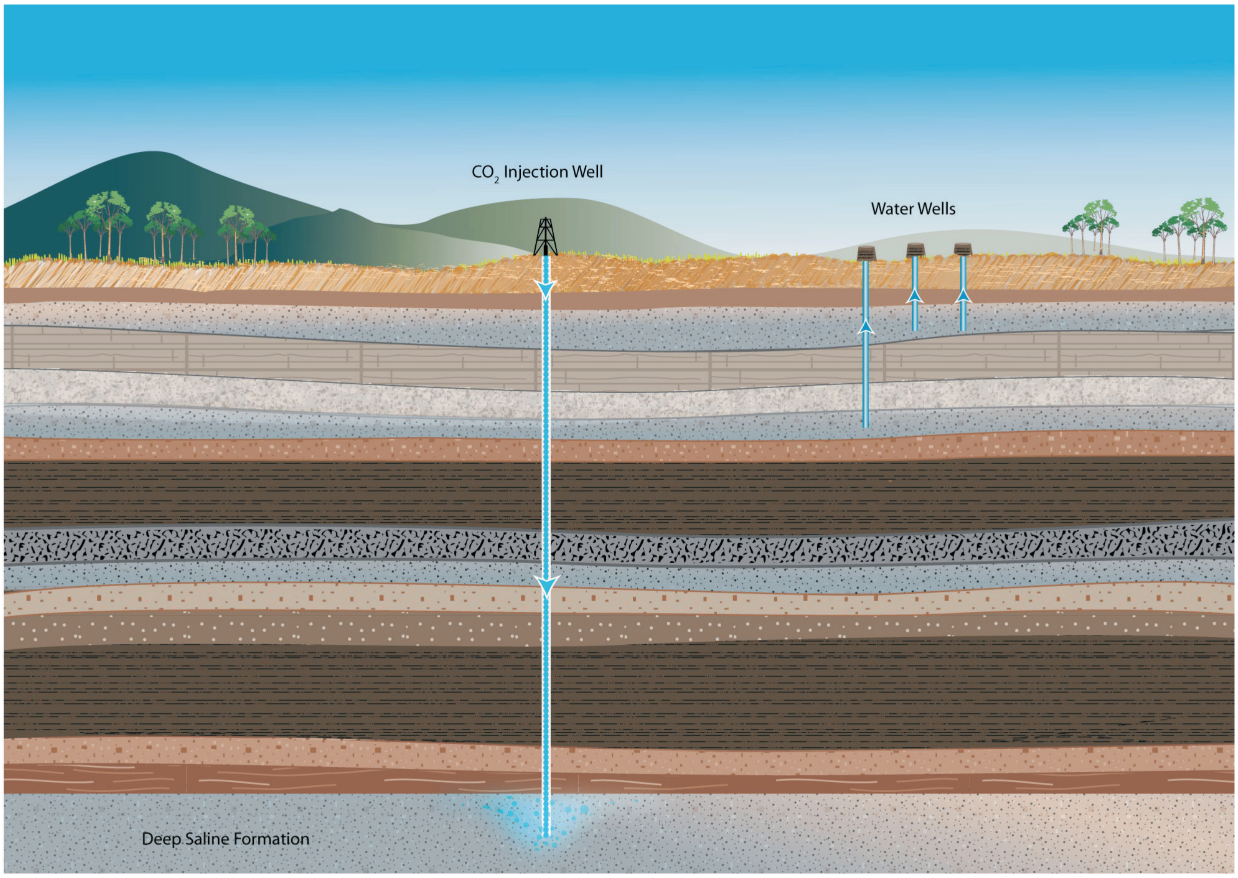
Healthy adults would have to be exposed to twelve times the normal atmospheric levels of CO_2 over several hours to feel any effect. Such exposure could cause headaches, drowsiness and lost concentration. Exposure to extremely high concentrations of CO_2—at least 150 times the level of CO_2 present in normal air—could lead to unconsciousness and ultimately asphyxiation, but this could be preceded by the obvious symptoms listed above.

Any CO_2 that is released from geologic storage is very unlikely to even approach minimally harmful levels. Moreover, technologies are available to monitor CO_2 levels and provide timely warning if CO_2 ever begins to be released. The closest monitoring, in some cases, may need to be where existing oil and gas wells penetrate the storage formation.

Will CO_2 Affect The Water Supply?

CO_2 injection will usually be much deeper (generally below 800 meters or 2600 feet) than usable sources of groundwater and will generally be separated by one or more layers of thick, impermeable cap rock. CO_2 injection is proposed for deep saline formations containing water, but this water is unusable because of its high salt and mineral content.

Given proper site selection and operation, the risks to usable water supplies would be extremely small. In the unlikely event that CO_2 would migrate upward toward shallower groundwater, seismic monitoring, groundwater analysis, and chemical tracers can detect any CO_2 that migrates upward into groundwater reservoirs and evaluate its effect on water quality.



Rock formations for geologic storage, such as deep saline formations, would be much deeper than any usable groundwater and separated from that groundwater by thick barriers of impervious rock. These formations generally already proved their effectiveness by keeping highly-salty saline water separate from usable groundwater for millions of years.

Image Source: CO2CRC

If CO_2 leaks into shallow groundwater, it could be removed, if necessary, by aerating the water and either using the water or re-injecting the CO_2 back into the storage formation. Aeration could also remedy any leakage into surface water supplies.

The combination of CO_2 dissolved in water is mildly acidic. In some cases, acidified water may very slowly dissolve metals and other minerals in adjoining rocks. Core samples from test wells can be examined to identify this possibility prior to injection. If it happens, several methods are available to correct the situation:

- The water may be pumped out and treated to remove the contaminants,
- Injection and extraction wells can be drilled to create a hydraulic barrier, and
- Passive methods utilizing natural biological processes can be employed.

Another potential risk to groundwater would arise if highly saline water (brine) were displaced into shallow drinking water aquifers. Ensuring that brine displacement does not occur is an important part of site characterization. For storage projects using a small fraction of the pore volume of the storage reservoir, brine displacement is not likely to be a serious concern.

HOW WILL STORAGE BE MONITORED?

Storage projects should be carefully tracked through Measurement, Monitoring and Verification (MM&V) procedures both during and after the period when CO_2 is being injected. These procedures address the effectiveness and safety of storage activities and the behavior of the injected CO_2 underground.

The objectives of MM&V will be to:

- ✓ Verify quantities of CO_2 injected and stored,
- ✓ Ensure the integrity of the injection well against leakage,
- ✓ Assure that the CO_2 remains in the intended subterranean geological formation,
- ✓ Detect leakages early enough for remediation to be effective,
- ✓ Monitor the effectiveness of any necessary remediation, and
- ✓ Make certain that abandoned wells are not leaking.

More MM&V activities are likely to be undertaken in research and development projects.

Types of Measurements

MM&V is used to measure the amount of CO_2 stored at a specific geologic storage site, to monitor the site for leaks or other deterioration of storage integrity over time, and to verify for accounting purposes that the CO_2 is stored and that it poses no harm to the host ecosystem. MM&V ensures safe permanent storage and can help satisfy regulators and government officials who must permit geologic storage projects. MM&V will also provide valuable feedback for continual refinement of injection and management practices.

Techniques for MM&V will, for the most part, be new applications of existing technologies. These technologies now monitor oil and gas fields and waste storage sites. They measure injection rates and pressures, subsurface distributions of CO_2, injection well integrity, and local environmental impacts.

<u>Injection rates and pressure measurements</u> are used to verify the amount of CO_2 injected and whether it is in a supercritical or gaseous state. Present technology can provide information on the state of the CO_2 (supercritical, liquid or gas) as well as an accurate measure of the amount of CO_2 injected.

<u>Subsurface distributions of CO_2</u> are measured to determine how the CO_2 is spreading through the reservoir and whether it is staying within the intended reservoir. A number of direct and indirect techniques exist for monitoring the subsurface distribution of CO_2. Direct techniques include the use of tracer gases to track the movements of the CO_2, measurements of water composition and subsurface pressure, the use of probes inserted in the well, and active seismic techniques. Indirect techniques include passive seismic monitoring, gravity and electrical measurements to detect the movements of CO_2, measurements of land surface changes and satellite imaging.

Underground water quality can be monitored for any changes due to CO_2 using specially-designed devices.

Image Source: Lawrence Berkeley National Laboratory and CO2CRC

Injection well integrity is evaluated to ensure that the operation does not result in leaks. Established techniques currently in use in the oil and gas industry can be used to monitor the integrity of CCS injection wells. Logging techniques, utilizing probes in the well, can be used to assess the bond and continuity of cement around the well casing. Similar probes to measure temperature and noises in the well are routinely used to detect well failures in natural gas storage projects and can be readily adapted for CCS projects.

Wireline logs are made by lowering instruments down the well to measure various properties of the rocks along its length.

Image Source: Copyrighted material, Schlumberger (used by permission).

Local environmental impacts are monitored to ensure that there is no effect on groundwater, air quality and/or plant and animal life. Methods are available to detect the effects of CO_2 migration by analyzing groundwater, air quality and ecosystems. Methods to detect CO_2 migration into groundwater include ongoing chemical analyses of water samples, and use of tracers in the injected CO_2. Migration of CO_2 into the atmosphere from geologic storage, if it occurs, is likely to be slow and, hence, unlikely to raise levels significantly above natural atmospheric levels. CO_2 levels in the air can be monitored by various types of chemical instrumentation. Effects of CO_2 on ecosystems can be determined by examining the productivity and diversity of plant and animal life. Other methods of evaluating possible CO_2 leaks include remote sensing, soil analyses and measurement of water quality.

This flux tower being installed at a geologic storage site measures the concentration of gases in the atmosphere. Such devices can detect increases in CO_2.

Image Source: CO2CRC

Post-injection Monitoring

Once CO_2 injection has stopped and the injection well sealed, some monitoring may continue to detect any CO_2 migration that might occur afterward. Although all the techniques previously discussed can be utilized for long-term monitoring, project developers will prefer those that are easily deployed and most cost effective. Since more secure storage mechanisms tend to have more effect over time, the need for monitoring will most likely decrease over time.

Current Status of Monitoring Technology

Although geologic storage monitoring is relatively new, most of the technologies needed are already in existence, having been developed for other purposes. Improvements for this application and new types of equipment are being rapidly developed. Work is currently being done on the design of overall monitoring networks. Further work is also being conducted to assess the need for long-term monitoring of injection sites after they have been closed.

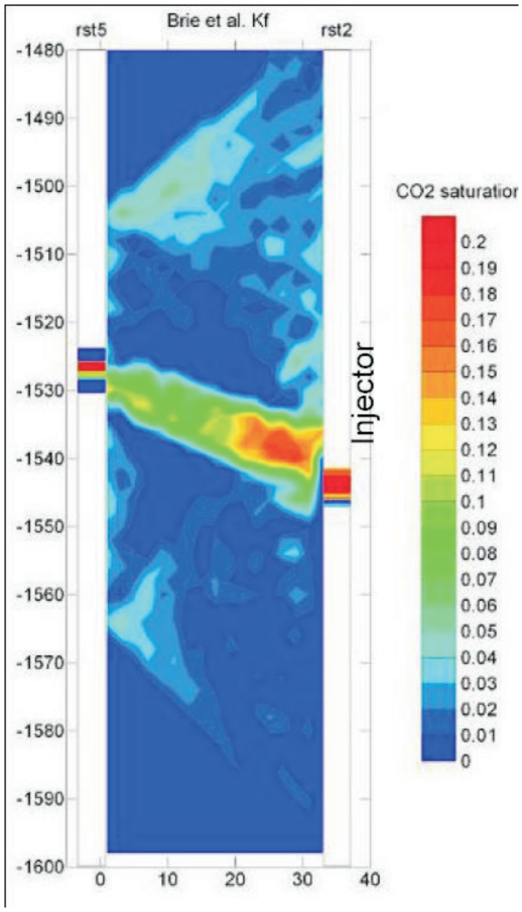
HOW CAN LEAKS BE FIXED?

Geologic storage sites should be chosen and projects operated to avoid leaks. Leaks can usually be prevented by thorough analysis of adequate geological information prior to injection, careful management of pressures during injection, good sealing during closure and effective MM&V during and after injection. In the unlikely event of a leak, however, methods are generally available to fix the problem. Responsibilities for such activities are set out in legal frameworks which are being developed in many jurisdictions.

CO_2 that is trapped by residual trapping, solubility/dissolution trapping, mineral trapping or inside the micropores of deep, unfractured coal seams is so tightly held that it not likely to move out of the storage formation. CO_2 that is kept in place primarily by stratigraphic or structural trapping, however, has the potential to move out of the storage formation if there are:

- ✓ Fractures in the cap rocks that may occur if the CO_2 is stored at too high pressure,
- ✓ Previously undetected pathways such as fractures or faults in the cap rock, or
- ✓ Poorly designed wells or badly sealed abandoned wells.

In deep coal seams, CO_2 has the potential to move out of storage through fractures in the coal seam that reach its top.



This is a picture created by seismic imaging of the dispersion of CO_2 injected into a saline formation. Such pictures and other monitoring techniques can detect movement of CO_2 out of the storage formation that can then be fixed.

Image Source: Frio X-well, Tom Daley, Mike Hoversten, L. Myer, Lawrence Berkeley National Laboratory.

Methods to Fix Leaks

Should movement of CO_2 from the storage reservoir occur during or after injection, methods are generally available to fix the leak. Most of these methods have long been used to fix leaks from other types of wells. A substantial base of experience has been gained over many years rectifying leakage from natural gas storage projects, subterranean liquid waste disposal projects, and groundwater and soil contamination from other sources. These techniques can also be used for CO_2, with the advantage that, unlike those other materials, CO_2 is not explosive or flammable, nor is it toxic at the concentration levels likely from a leak. It is reasonable to expect that these techniques would work for CO_2. They have not yet been used for this purpose, however, primarily because it has not been necessary to fix leaks at existing geologic storage projects.

Leaks can generally be expected to be eliminated by reducing injection or storage reservoir pressures or by adjusting pressures in different parts of the reservoir. Leaks may also be eliminated by stopping injection at the current site and resuming it at a more suitable site.

Leaks into the soil, atmosphere or groundwater can be safely dissipated or the CO_2 can be collected and re-injected. Although dissipation into the atmosphere reduces the effectiveness of CCS, the expectation is that the need to take such an action will be very rare. In any event, the leak will not likely pose any danger to humans or the environment because, other than possibly through improperly sealed wells, the leaks will probably be very slow and the resulting concentrations well below harmful levels. Particular care, however, needs to be taken in low-lying or enclosed areas where CO_2, which is heavier than air, may tend to accumulate.

Leaks from abandoned wells may present the most significant vulnerability in some areas. These can usually be sealed with heavy mud or cement. If the abandoned well to be sealed, however, is not accessible on the surface, another well can be drilled nearby to intercept the leaking well and seal it by pumping mud down the injection well. If the injection well itself leaks, it can be repaired by replacing parts of the well or injecting cement to seal the leaks. If necessary, the well can be properly sealed and abandoned. These are standard and long-established techniques for sealing leaking wells. Many countries have established procedures for abandonment of oil, natural gas and other mineral extraction wells that can be applied to CO_2 injection.

Due to the trapping mechanisms utilized by geologic storage and the dispersion of the injected CO_2, any movements from the storage formation are likely to be slow, allowing time to make repairs before any damage is done. Appropriate monitoring techniques are needed to ensure that any migration is caught early.

Who is Responsible?

In a geologic storage project, some party or parties must be responsible for effective planning, safe and secure operation, detecting and fixing any migrations that occur and repairing any adverse impacts, however unlikely. Who those parties are depends on the project operator and the applicable legal system, which varies by jurisdiction.

CCS is a new type of activity and legal frameworks for it are evolving. In countries where extensive oil and gas production activities take place (in particular, EOR or acid gas injection), the legal framework may be relatively well advanced due to the similarity of CCS to those activities. In other jurisdictions, less of the legal framework may be in place.

Storage in geologic formations under the ocean is governed by various international treaties, most notably the London Convention, which covers every ocean in the world. In addition, other treaties govern specific ocean regions. The London Convention and its 1996 Protocol, (known as the London Protocol) in particular, govern marine pollution and ocean dumping. The governments that are parties to the London Protocol agreed in 2006 to allow injection of CO_2 in sub-seabed geologic formations.

The project operator will usually have the primary responsibility to effectively plan the project, obtain the necessary permits, operate the injection facilities safely and close the facilities properly when the injection period is over. Monitoring and remediation responsibilities may vary, especially post-injection. Parties with post-injection responsibility may include the operator, governments, a third party brought in under contract, or some combination, all subject to the prevailing legal framework. This may also change over time.

Government organizations—which vary by jurisdiction—may have oversight for various aspects of the CCS project, including the procedures used, health and safety, liability, protection of water supplies and monitoring. The responsibilities and obligations are still evolving in some jurisdictions. According to the IPCC Special Report on Carbon Dioxide Capture and Storage, the following legal and regulatory issues need to be considered:

- The role of pilot and demonstration projects in developing regulations;
- Approaches for verification of CO_2 storage for accounting purposes;
- Approaches for regulatory oversight of selecting, operating and monitoring CO_2 storage sites, both in the short and long term;
- Clarity on the need for and approaches to long-term stewardship; and
- Requirements for decommissioning of a storage project.

QUESTIONS TO ASK PROJECT DEVELOPERS

The best assurance of safe and secure geologic storage is a project that is well designed and carried out. The answers to the following questions, taken together, can provide some of the basic information to determine whether that is being done. This booklet provides a relatively non-technical perspective on the issues these questions address. A thorough and accurate evaluation, however, requires substantial expertise in geology and geological engineering as well as detailed information on the proposed storage sites.

1. How much CO_2 will be injected, at what rate, and over what period?
   - How might this vary?
   - What impurities, if any, will the CO_2 stream contain?
   - What safety precautions will be undertaken on the surface at the injection site?

2. Into what geologic formation will the CO_2 be injected?
   - What is the type of rock, thickness and extent of the geologic formation?
   - Where will the CO_2 be injected?
   - How deep is the storage formation where it will be injected?

3. What alternative sites were considered for CO_2 storage and injection?
   - Why were this storage reservoir and injection site(s) selected?

4. What studies were conducted of the storage reservoir and the alternatives?
   - What measurements were taken and analyses performed using these results?
   - Does the reservoir have enough storage capacity to meet foreseeable needs?
   - What level of confidence do the results provide?

5. How will the CO_2 be trapped in this formation and what evidence do you have that the trapping will be effective?
   - What trapping mechanisms exist within the storage formation?
   - What is the primary seal and its thickness?
   - Are there any secondary seals and what are their thicknesses?
   - Do any faults or fracture zones intersect the primary or secondary seals?
   - Is the injection pressure below what would affect the cap rock primary seal?
   - Do any active or abandoned wells penetrate the primary or secondary seals?

6. What seals exist between the storage formation and any usable groundwater?
   - What is the condition of those seals (e.g., faults, fractures, penetrations)?

7. What monitoring activities during and after injection will be conducted and by whom will those be performed?

8. Who will be liable for leaks and what will be done by whom to fix any detected leaks both during and after injection?

9. What precautions will be taken at project closure to ensure continued safe storage?

10. What aspects of the project are regulated and under what regulatory authority?
    - What are the specific laws and regulations that govern geologic storage?
    - Have all necessary legal and regulatory approvals been obtained?

NOTES

Carbon Capture and Storage

MEETING THE CHALLENGE OF CLIMATE CHANGE

IEA GREENHOUSE GAS R&D PROGRAMME

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International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an international energy programme. The IEA fosters cooperation amongst its 26 member countries and the European Commission and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

IEA Greenhouse Gas R&D Programme

This booklet is a non-technical summary for general informational purposes and should not be relied on for the detailed and specific information necessary to evaluate specific carbon capture and storage projects. The views and opinions of the authors expressed herein do not necessarily reflect those of the IEA Greenhouse Gas R&D Programme, its members, nor any employee or persons acting on behalf of any of them. In addition, none of these persons makes any warranty, express or implied, assumes any liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product or process disclosed or represents that its use would not infringe privately owned rights, including any party's intellectual property rights. Reference herein to any commercial products, process, service or trade name, trademark, or manufacturer does not necessarily constitute or imply an endorsement, recommendation or any favouring of such products.

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Contents

Executive Summary

Avoiding severe global climate change is an enormous challenge. Greatly reducing man-made carbon dioxide (CO_2) emissions is central to meeting that challenge.

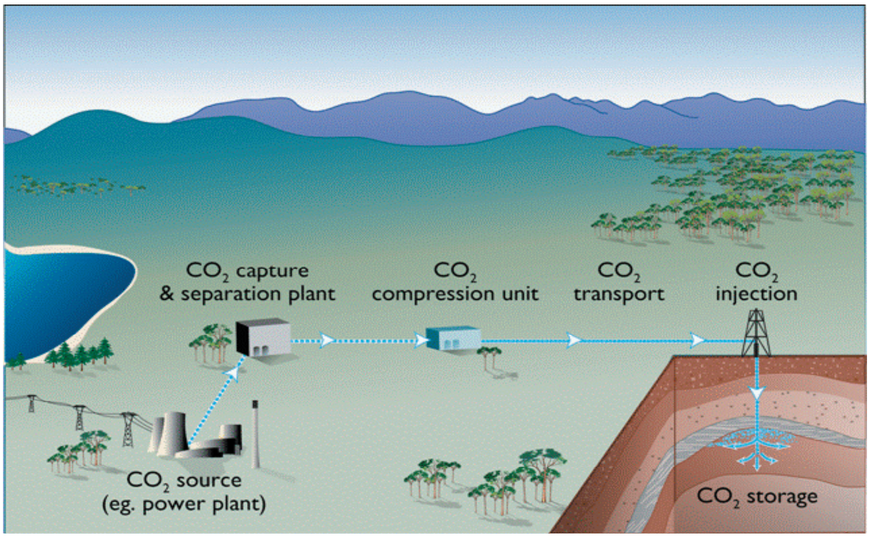
Carbon Dioxide Capture and Storage (CCS) is one of the measures necessary to reduce CO_2 emissions. CCS is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent storage of that CO_2 in deep underground rock formations. CCS is an integrated system with three stages: capture from a source, transport and geologic storage.

Why CCS Is Needed

Over the next half century, the use of widely-available and relatively inexpensive fossil fuels for power generation and industry is likely to grow substantially throughout the world and particularly in developing countries. Growing fossil energy use, however, could greatly increase CO_2 emissions. Yet, the Intergovernmental Panel on Climate Change (IPCC) projects that 2000 emission levels must be cut by half or more by 2050 to avoid the most serious consequences of climate change. CCS is the only technology that will enable large-scale fossil fuel power generation and several vital industries to continue to be economically viable while reducing their CO_2 emissions in a carbon-constrained world.

Cost of CCS

The cost of CCS varies widely with the CO_2 source, the capture method, the distance to the storage site and the characteristics of the storage reservoir. Most of the cost is in the capture stage. CCS costs are expected to decrease with technology development and experience. When commercial, CCS costs will likely be well within the range of many of the other measures necessary to mitigate climate change—less expensive than some, more expensive than others.



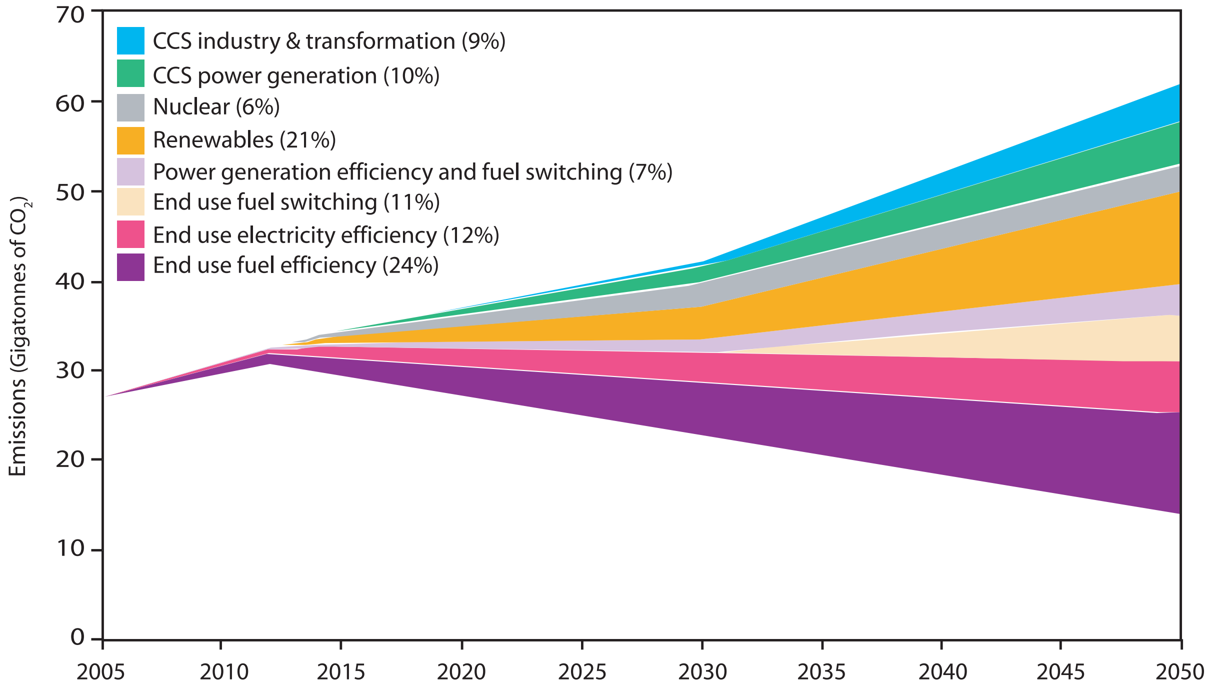
In CCS, CO_2 is captured before it can be emitted into the atmosphere. It is then compressed and transported to the injection site. The CO_2 is injected into deep underground rock formations, where storage is monitored and verified.

Image Source: CO2CRC

CCS will be a highly cost-effective emissions reduction measure. According to a study by the International Energy Agency, CCS in the power generation and industrial sectors is anticipated to create 19 percent of CO_2 emissions reduction needed in 2050 for only 6.7 percent of the required investment in CO_2 emissions reduction. The same study also shows that the cost of cutting CO_2 emissions in half by 2050 would nearly double without CCS.

Readiness of CCS

Each CCS stage has been used separately for decades for other purposes. The first commercial, integrated CCS projects are now in operation. These projects are in a few industrial applications such as natural gas processing and ammonia production. The first commercial CCS projects in the power sector will likely go on line in the 2010s. CCS can be ready for widespread commercial use in power generation by about 2020 and widespread commercial use in industry somewhat later. That timeframe will enable CCS to contribute a major share of the needed emissions reduction.



An analysis by the International Energy Agency shows that CCS in both power generation and industry, when implemented along with energy efficiency and renewable energy sources, can create most of the emissions reductions needed to cut emissions in half by 2050. CCS alone can create 19 percent of the emissions reduction in 2050.

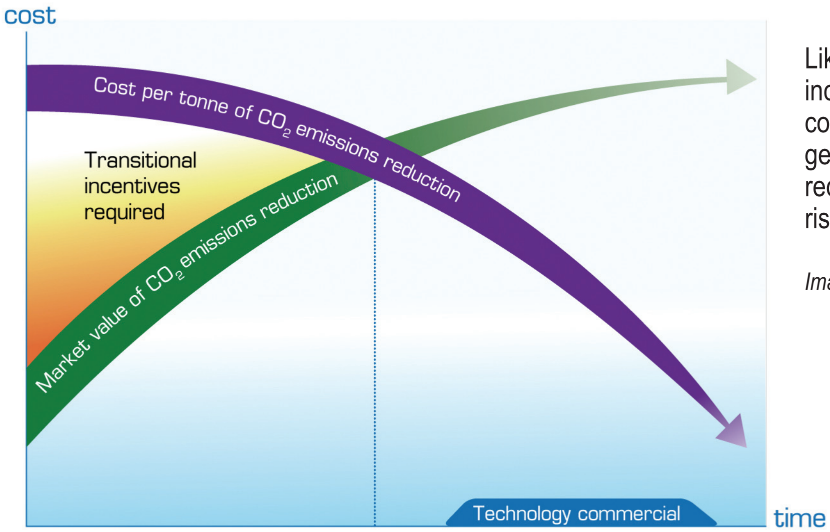
Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

Coal Gasification Plant with CO_2 Capture

CO_2 Storage Injection Site

CO_2 has been captured since 2000 at this commercial coal gasification plant in North Dakota, USA, and piped to Saskatchewan, Canada, where it is stored in depleting oil fields. Currently, 2.8 million tonnes per year of CO_2 are disposed of in this way. Many other CCS projects will become commercial in the coming years.

Image Sources: Dakota Gasification Company and IEA Weyburn-Midale Monitoring Project, Final Phase.



Like other emissions reduction measures, transitional incentives will be required before CCS becomes commercially viable in applications such as power generation. Such incentives will no longer be required when the value of CO_2 emissions reduction rises above the cost of CCS.

Image source: Bluewave Resources, LLC and CO2CRC.

Most commercial projects will be new facilities designed with CCS. Some new power plants built as capture-ready and some currently-existing facilities will likely be suitable for CCS retrofitting. Capture-ready power plants are plants built without capture, but which have the capability of being retrofit when the necessary regulatory and economic drivers are in place. Specifications for what makes a plant capture-ready are now being developed.

CCS will become widely commercially viable when the cost of CO_2 emissions—as set, for example, by the price of allowances in an emissions trading program or by a carbon tax—is above the cost of CCS. The cost of CCS is also expected to decline as the technology is developed and there is more experience using it. Until then, transitional incentives will be needed to ensure that demonstration and early commercial projects are developed. Renewable energy technologies, such as solar and wind power, similarly need early incentives.

What It Will Take

Further progress will be required to achieve the timely and widespread commercial use of CCS. Both technical progress and the development of enabling institutional frameworks will be needed.

The major technical requirements for broadening the use of CCS are reducing capture costs, demonstrating long-term storage in diverse geological settings, integrating the entire system, and achieving scale. All are considered to be achievable in the near future. Meeting these requirements necessitates further research and development; fully-integrated, commercial-scale demonstration projects; and participation by both government and the private sector.

Intensive work is being done around the world to advance CCS technology. Rapid technical progress is already improving effectiveness, efficiency and cost, as well as applicability to different emission sources and geologic formations. A large and growing number of scientists, engineers and geologists now devote their efforts to all aspects of CCS. CCS has become a high priority for many governments and companies. Major international collaborations are taking place.

Enabling institutional frameworks would consist of effective and appropriate laws and regulations, private and public sector institutions that can implement and finance CCS, and public understanding and support for CCS. Efforts are underway in many countries to develop each of those.

Reflecting the importance now being given to CCS, the G8 leaders at their 2008 meetings in Japan supported actions to advance CCS globally, including the development of at least 20 fully-integrated, commercial-scale demonstration projects.

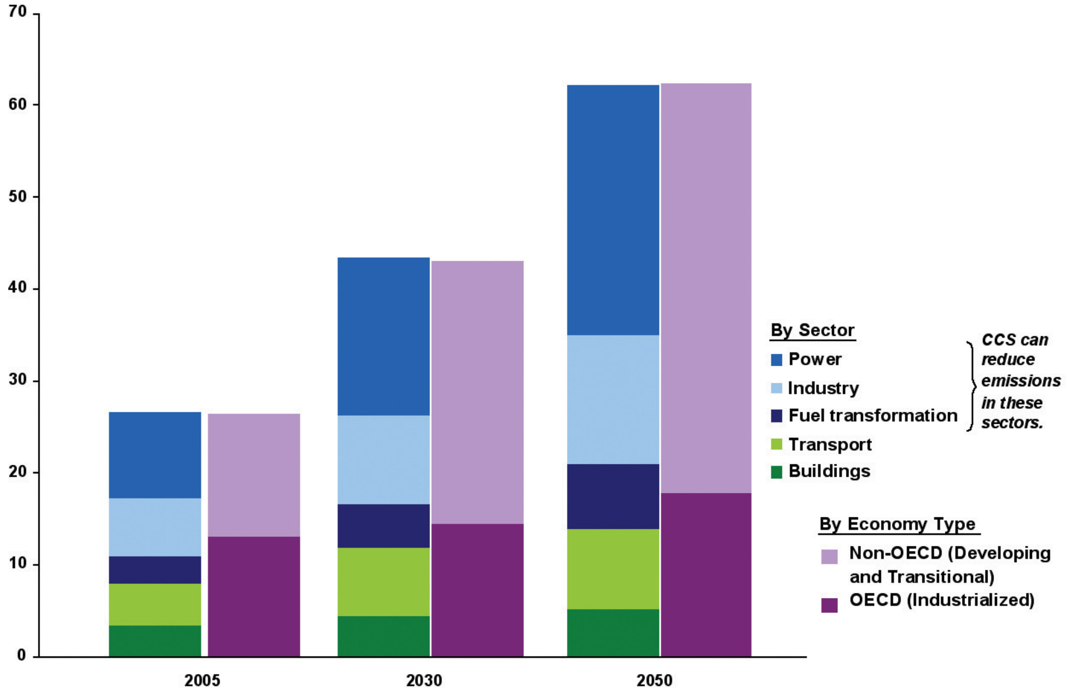
CCS can be an important, cost-effective and timely part of the solution to climate change. Making CCS widely commercially viable by about 2020 is achievable with sustained, global efforts by governments and industry. Such efforts are now underway throughout the world.

Carbon Capture and Storage can be an important, cost-effective and timely part of the solution to climate change.

Why Carbon Dioxide Capture and Storage is Needed

Carbon Dioxide Capture and Storage (CCS) is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent disposal of that CO_2 in deep underground rock formations. CCS is one of many actions necessary to stabilize greenhouse gas concentrations in the atmosphere. It will significantly reduce emissions from the power generation and industrial sectors, a fact that is being increasingly recognized and acted upon throughout the world.

Avoiding severe global climate change is an enormous challenge. Greatly reducing man-made carbon dioxide (CO_2) emissions is central to meeting that challenge. The Intergovernmental Panel on Climate Change (IPCC) estimates that CO_2 emissions must be reduced 50 to 85 percent by 2050 compared to 2000 levels. That reduction will keep the global mean temperature rise below 2.0 to 2.4^{o}C, where severe impacts begin. Yet, the trend in global CO_2 emissions is a continued rapid rise for the foreseeable future. To date, industrialized countries have emitted most of



Current trends in global CO_2 emissions to 2050: Rising significantly. Most of this increase will be primarily in developing countries.

Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

the CO_2. Emissions from developing countries, however, are growing much faster and their emissions will overtake those of the industrialized countries in the near future.

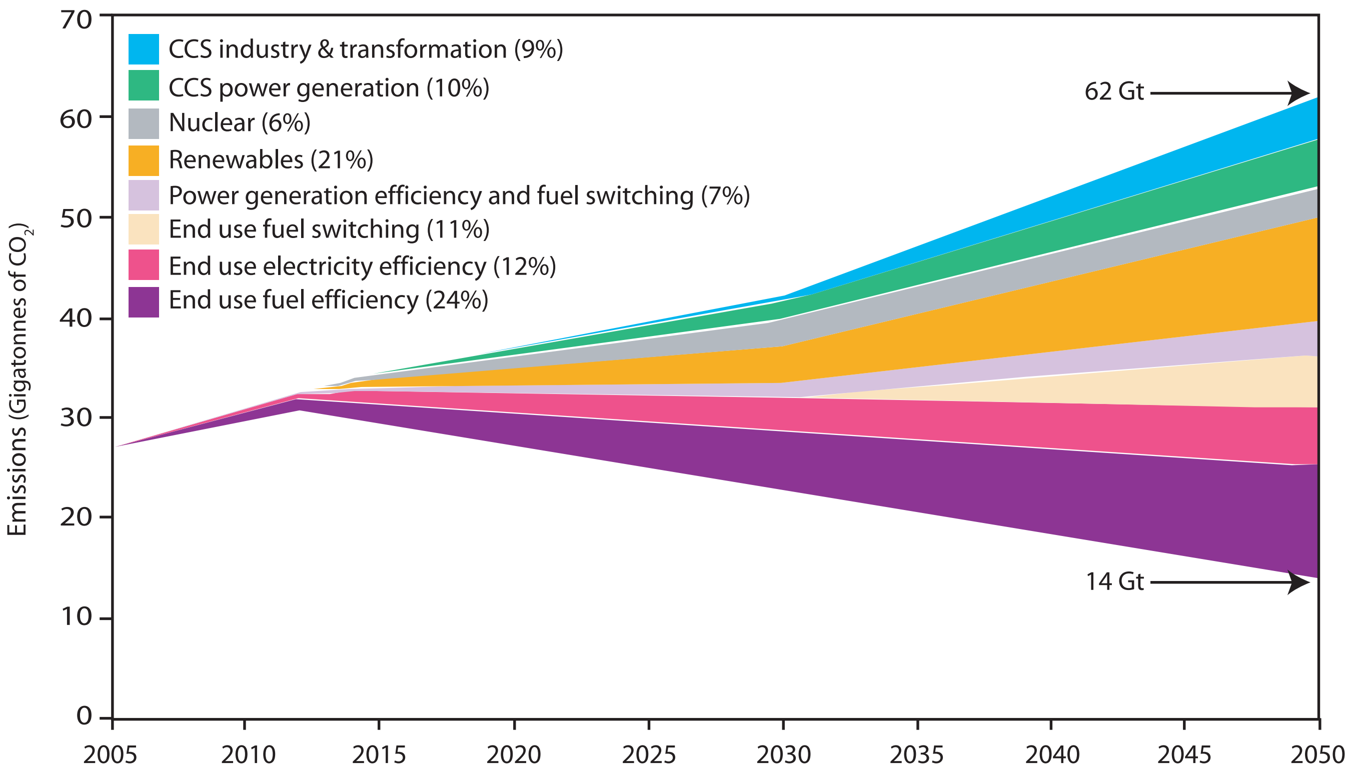
The scale of the required reduction in CO_2 emissions is enormous. Adequately reducing CO_2 emissions will require global efforts in virtually every economic sector—power, industry, fuel transformation, transport, and buildings—in both industrialized, transitional and developing economies. Human activity globally currently releases about 28 gigatonnes of CO_2 ($GtCO_2$) per year into the atmosphere. Cutting this in half or more would bring emissions to 14 $GtCO_2$ or below by 2050. This is a reduction of at least 48 $GtCO_2$ below the 62 $GtCO_2$ projected for 2050 under current trends. Cumulatively, at least about 600 Gt will have to be cut over the entire period.

How big is a gigatonne of carbon dioxide (1 $GtCO_2$) emissions reduction?

A Gt is 1 billion (10^9) tonnes (metric tons) or 10^{12} kilograms. (1 kilogram = 2.2 pounds) But what does 1 $GtCO_2$ really mean in terms of emissions reduction? Emissions reduction of 1 $GtCO_2$ per year is the equivalent of:

- ✓ Building 1,036,000 Megawatts (MW) of wind farms (current world total: 14,000 MW);
- ✓ Applying CCS to 137 coal plants, each 1,000 MW (11 percent of the current world total);
- ✓ Increasing efficiency of the world's 500 million automobiles by 7.3 km/liter (10.8 mpg);
- ✓ Reforestation of 90,000,000 hectares (222,390,000 acres), about 10 percent of the area of Brazil; or
- ✓ Biomass plantations on 48,000,000 hectares (118,000,000 acres), about the area of Spain.

If all five of these measures were implemented for 30 years, that would be 150 $GtCO_2$, about one quarter of the minimum needed.



An analysis by the International Energy Agency shows the measures needed to cut emissions in half by 2050. Most of the needed emissions reduction can be achieved by CCS in the power generation and industrial sectors, energy efficiency and renewable energy sources.

Image Source: Based on International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

Many different measures are necessary to reduce greenhouse gas emissions. These measures include increasing energy efficiency in all sectors; using renewable energy sources such as wind, biomass, geothermal and solar energy; switching to low- or no-carbon fuels; and implementing carbon dioxide capture and storage. It is also necessary to reduce emissions of other greenhouse gases such as methane and nitrous oxide and to enhance natural sinks for CO_2 such as rainforests.

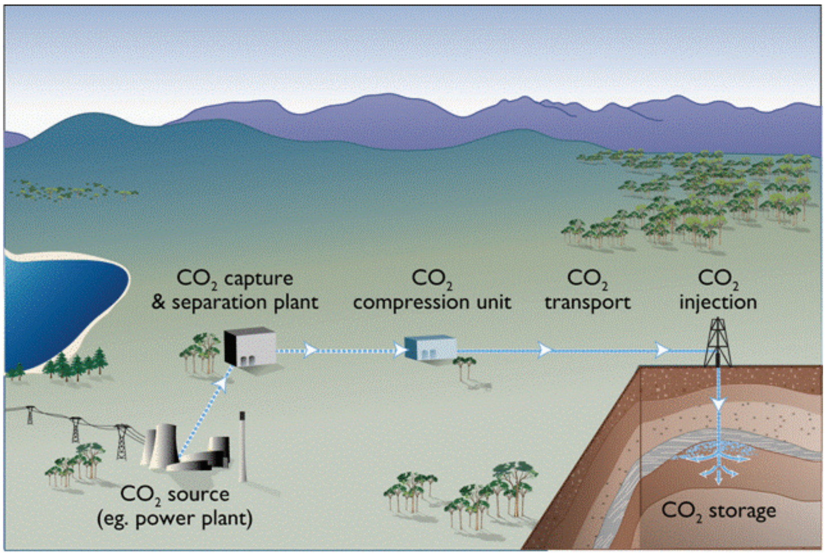
The Role of Carbon Dioxide Capture and Storage

Carbon Dioxide Capture and Storage (CCS), also known as Carbon Capture and Sequestration, is the separation and capture of CO_2 from power generation or industrial processes and the transport and permanent storage of that CO_2 in deep underground rock formations. By preventing CO_2 emissions from large facilities from entering the atmosphere, CCS is potentially a powerful tool for combating climate change.

CCS has three basic stages: capture, transport and geologic storage. All three are evolving rapidly as research and development proceeds. Many technology options for capture are emerging; most CO_2 will be transported by pipelines; and knowledge of how to conduct geologic storage is increasing.

In CCS, CO_2 is separated from other gases at a large facility such as a power plant before it is emitted into the atmosphere. The CO_2 is then compressed into a very dense supercritical fluid state and, if necessary, transported for injection. At the injection site, the supercritical fluid CO_2 is injected under high pressure into a deep underground geologic formation for very long-term storage. That geological formation may be a deep saline formation or a depleting oil or natural gas field at least 0.8 kilometers (2,600 feet) below the surface of the earth where the pressure will ensure the CO_2 will stay in a supercritical fluid state. CO_2 may also be stored in unmineable coal seams at somewhat shallower depths using a different storage process.

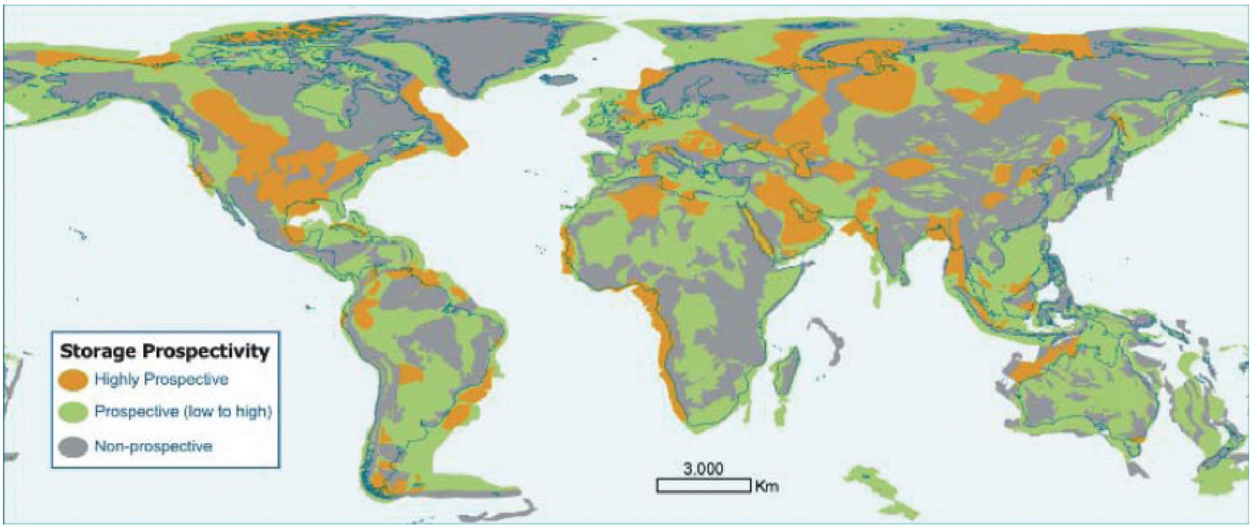
The Annex "Advancing CCS Technology" provides a detailed explanation of how CCS works and how it is being improved.



In CCS, CO_2 is captured before it is emitted into the atmosphere, compressed, transported to the injection site and then injected underground in suitable deep rock formations.

Image Source: CO2CRC

Most credible projections indicate that fossil fuels will continue to be the world's dominant energy source until at least mid-century. Even with recent price increases, fossil fuels are abundant and relatively low cost. As a result, most countries will not be able to substantially reduce their dependence on fossil fuels over the next several decades. Renewable energy sources may take decades to significantly penetrate the global energy market. Developing countries, particularly China and India, have made huge



Prospective sites to store CO_2 are located throughout the world.

Source: Bradshaw, J. and Dance, T. (2004): "Mapping geological storage prospectivity of CO_2 for the world's sedimentary basins and regional source to sink matching," in (E.S. Rubin, D.W. Keith and C.F. Gilboy eds.), GHGT-7, Proc. Seventh International Conference on Greenhouse Gas Control Technologies, Vancouver, B.C., Canada, September 5-9, 2004.

strides in developing their economies and need inexpensive energy to continue development. They will continue to use fossil fuels.

CCS is one of many measures needed to combat climate change. Each measure is necessary but, by itself, insufficient. Each measure addresses only part of the problem. Many measures are necessary to create the required total cumulative emission reduction. All are needed.

Other than increasing efficiency, CCS is the only CO_2 mitigation measure that reduces emissions from large stationary industrial sources that utilize fossil fuels. CCS can prevent further destabilization of the climate from the continued use of fossil fuels and can be a bridging technology to widespread use of renewable and alternative energy sources. Used with sustainable biomass, CCS can make an even greater contribution to reducing the concentrations of CO_2 in the atmosphere by actually removing atmospheric CO_2.

CCS is needed to reduce CO_2 emissions in several energy and process industries. The industries from which CO_2 may be captured include power generation, oil and gas production, iron and steel, cement, chemicals, and pulp and paper. These industries are vital to both economic and human welfare in industrialized and developing countries. CCS is the only means for these industries to continue operation while still substantially reducing CO_2 emissions beyond reductions through increasing efficiency and switching to low-or no-carbon energy sources. Not having CCS available would significantly increase cost, difficulty and time required to achieve the required emissions reduction.

The IPCC has identified nearly 7,900 existing sources as potential candidates for CCS. Each emits over 0.1 million tonnes per year of CO_2. These have total emissions of 13.5 $GtCO_2$ per year, nearly half of the current total of man-made emissions. This is shown in Table 1.

Many more large stationary sources are expected to be built in the coming decades, especially in developing countries. Most of these large stationary sources are power plants, but many others are industrial facilities in various process industries as well as extractive industries such as oil and gas production. In power generation, CCS can reduce CO_2 emissions from plants that burn fossil fuels or biomass. CCS can also be used for large biomass fermentation or bioenergy facilities that emit large amounts of CO_2. Most CCS is likely to be used for new facilities, but under the right conditions, it may be retrofit to existing facilities. Retrofits may be more difficult because most existing facilities were not designed for CCS, may not have the space and were not sited with proximity to geologic storage in mind.

CCS is anticipated to be capable of removing a large amount of the CO_2 that would otherwise be emitted into the atmosphere from large power generation and industrial sources. IEA projects that by 2050, CCS for power generation could remove about 4.8 $GtCO_2$ per year and CCS for other industrial sources could remove about 4.3 $GtCO_2$ per year. Together, that would be about 19 percent of the total emissions reduction needed in that year (48 $GtCO_2$) to stabilize the climate.

Suitable geologic formations are located all over the world. Likely global storage capacity is estimated to be equal to several hundred years of the total emissions from potential sources. The IPCC estimated storage capacity at a minimum of 1,678 $GtCO_2$ and potentially much higher. Current emissions from large stationary sources are 13.5 $GtCO_2$ per year.

Need for CCS: Increasingly Recognized

The need for CCS to reduce CO_2 emissions from large stationary facilities is being recognized. CCS was first seriously considered as an option for reducing CO_2 emissions in the mid-1990s. At that time, it was generally perceived to be a highly speculative concept. Few scientist and engineers were working on it and it was not a priority for any governments or private companies. The first major commercial CCS project, Sleipner, began operation in 1996 in response to a carbon tax imposed by the Norwegian government on offshore oil and gas production.

Since those early days, extensive work efforts have gone into CCS. The results so far have been highly positive: a profusion of technology options emerged; several commercial projects began operation, are under construction or are planned; and CCS is now a high priority for many governments and companies.

Today, governments, research institutions, industrial firms and environmental groups in both industrialized and developing countries are working to bring CCS into widespread commercial use. Thousands of engineers and scientists are now focusing their efforts on CCS. CCS is increasingly supported by experts on climate change. Initiatives such as the IEA Greenhouse Gas R&D Programme (IEAGHG) and the Carbon Sequestration Leadership Forum (CSLF) are fostering international collaboration. The goal is for CCS to enter widespread commercial use by about 2020, about a dozen years from now.

Table 1. Potential Capacity for Geologic Storage ($GtCO_2$)

Reservoir Type	Lower Estimate	Higher Estimate
Oil and Gas Fields	675*	900*
Unmineable coal fields	3 to15	200
Deep Saline Formations	1,000	Uncertain but possibly 10,000

*These numbers would increase by 25 percent if “undiscovered” oil and gas fields are included in this assessment.

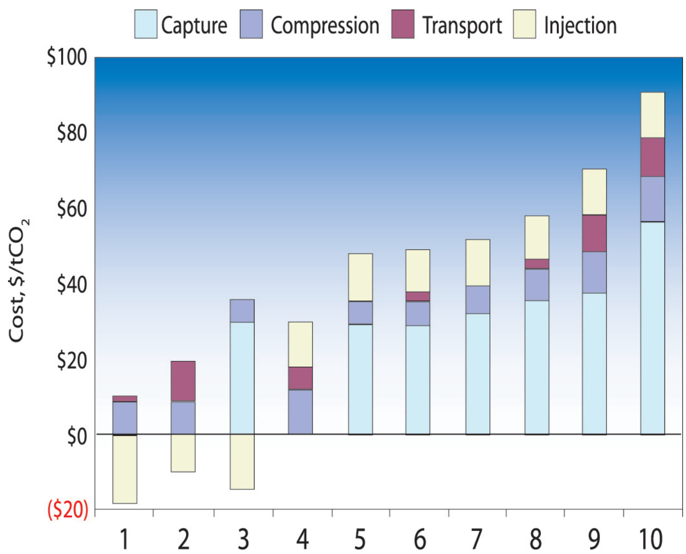
Source: IPCC, Special Report on Carbon Dioxide Capture and Storage, 2005. (The estimates in this 2005 report are based on published sources now several years old. Since then, considerable effort has gone into exploration and estimates today would probably be much higher.)

Cost of CCS

The cost of CCS varies widely among projects. The affordability of CCS depends on its cost compared to the costs of the other greenhouse gas abatement options needed to adequately cut emissions. It will likely be more expensive than some other options and less expensive than others. Future costs are likely to be reduced as the result of R&D as well as incremental improvements.

The costs of all three CCS stages—capture (including compression), transport and storage—vary considerably. Accordingly, so does the cost of the total system. The cost of CCS depends on many factors. These factors include type and size of source, type of capture process, distance to injection site, location onshore or offshore, injection depth, required monitoring, and level of integration. For sources such as power plants, capture is the dominant cost element. It accounts for 70 to 80 percent of total costs, although this percentage varies substantially. The range of total costs for CCS systems is wide, from negative (i.e., making a profit through CO_2 sales) to quite high.

Near-term opportunities for commercially-viable CCS projects tend to have low capture costs and substantial revenues from sales of the captured CO_2. Facilities with low capture costs have a CO_2 stream that is highly concentrated and already at high pressure. Examples include facilities whose commercial purpose is to separate CO_2 from natural gas as well as ammonia and hydrogen production facilities. CO_2 may be injected into depleting oil fields to increase production in a process known



1. **High purity ammonia plant** nearby, EOR
2. **High purity natural gas processing facility** moderately distant, EOR
3. **Large coal-fired power plant** nearby, ECBM
4. **High purity hydrogen production facility** nearby, depleted gas field
5. **Large coal-fired power plant** nearby, deep saline formation
6. **Coal-fired power plant** moderately distant, depleted gas field
7. **Iron and steel plant** nearby, deep saline formation
8. **Smaller coal-fired power plant** nearby, deep saline basalt formation
9. **Cement plant** distant, deep saline formation
10. **Gas-fired power plant** distant, deep saline formation

The total cost of CCS and its components varies with the location and source as well as the distance to and type of storage. At the low end is a negative total cost (a net profit) for an ammonia plant with nearby EOR. Such plants already operate commercially. At the high end is a natural gas plant distant from a saline formation. Costs will decline as CCS technology matures. (These cost estimates are for sites in the United States using technologies and costs as of 2006. These costs are now out of date but illustrate the wide range and diverse makeup of potential CCS costs.)

Source: JJ Dooley et al. "Carbon Dioxide Capture and Geologic Storage: Core Elements of a Global Energy Technology Strategy to Address Climate Change," Battelle Memorial Institute, April 2006.

as Enhanced Oil Recovery (EOR). Similarly, CO_2 may be injected into depleting natural gas fields in Enhanced Gas Recovery (EGR) or into methane-bearing coal seams for Enhanced Coal Bed Methane (ECBM). Revenues can be earned by selling the CO_2 for EOR, EGR or ECBM.

Cost-Effectiveness of CCS

CCS is a cost-effective measure to reduce CO_2 emissions compared to other needed CO_2 abatement measures. Energy Technologies Perspectives, 2008, a comprehensive study of the global role of technology in a sustainable energy future,[1] clearly shows the cost-effectiveness of CCS. This study projects the measures and technologies required to reduce CO_2 emissions by half or more by 2050 (the minimum goal set by the IPCC) for the lowest cost. It then identifies the work activities needed to commercialize the full set of required technologies quickly enough to achieve that reduction. All major economic sectors— transportation, buildings, industry, energy transformation and power—are considered. The study compares three future scenarios:

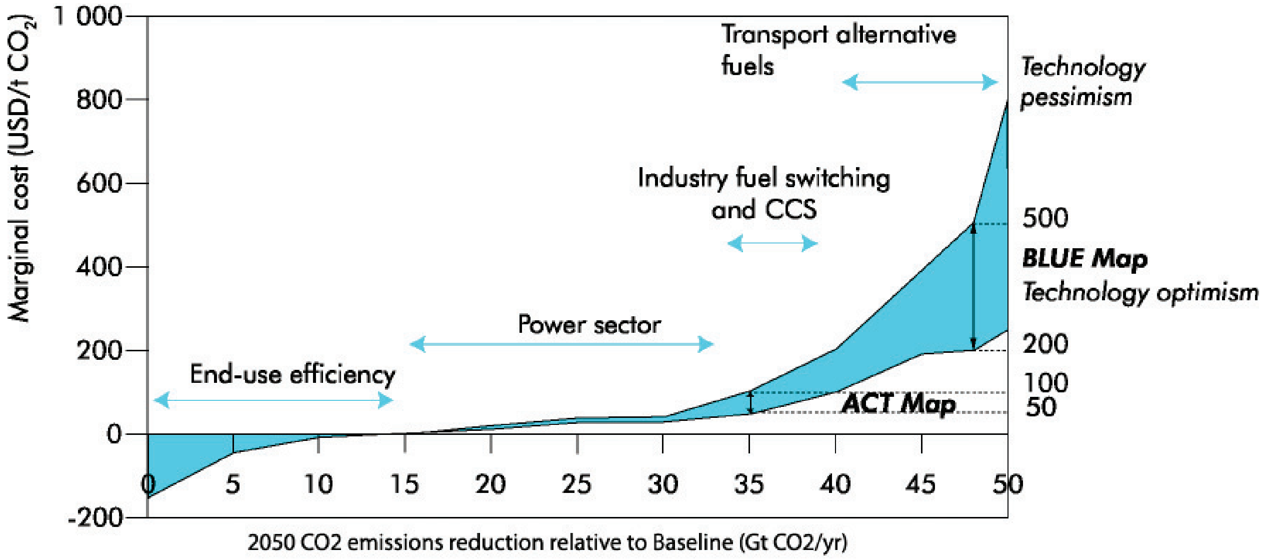
1. The Baseline scenario represents the current, unsustainable trends of rising energy consumption and CO_2 emissions. In this "business-as-usual" scenario, CCS and other advanced technologies do not reach widespread commercial use. Global CO_2 emissions rise to 62 $GtCO_2$ per year by 2050.
2. In the ACT Map scenario, only technologies that already exist or are in an advanced state of readiness are used to bring CO_2 levels back to 2005 levels by 2050. This is not sufficient to meet even the minimum IPCC goal.
3. In the BLUE Map scenario, emissions are cut to 50 percent of 2005 levels (about 14 $GtCO_2$ per year) by 2050 through new technologies such as CCS and the "urgent implementation of unprecedented and far-reaching new policies in the energy sector." The total emissions reduction in 2050 is 48 $GtCO_2$ per year—sufficient to reach the minimum IPCC goal.

CCS is only one of many technologies considered in the Energy Technologies Perspectives, 2008 study. Both the ACT Map and BLUE Map scenarios require substantial investment (US$17 trillion and US$45 trillion respectively through 2050) in a wide variety of technologies. The BLUE Map scenario, in particular, requires extensive efforts to develop a broad portfolio of technologies, not just CCS. For both the ACT Map and BLUE Map scenarios, the range of abatement costs is estimated under two sets of assumptions about technology trends: "technology optimism" and "technology pessimism."

The cost of CCS is in the mid-range of the needed emissions reduction measures. The range of costs of measures for reducing emissions under both the optimistic and pessimistic cases in both the ACT Map and BLUE Map scenarios are shown in the figure on page 8. The least-cost measures in all cases are to increase end-use efficiencies, but increasing efficiency is not sufficient to adequately reduce emissions. Power sector measures (mostly CCS) are needed under both optimistic and pessimistic assumptions. In both scenarios, they are in a cost-effective range.

The same study shows that the cost of reducing CO_2 emissions to half their current level would nearly double without CCS (US$394 per tonne versus US$200 per tonne). As Table 2 shows, if CCS does not become available, emissions will be nearly 50 percent higher at the cost of US$200 per tonne (20.4 versus 14.0 $GtCO_2$ per year).

[1] International Energy Agency, Energy Technology Perspectives, 2008: Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008.



This figure from Energy Technology Perspectives, 2008 shows why CCS will be a cost-effective measure for cutting emissions in half by 2050 (a 48GtCO_2 per year total emissions reduction called the BLUE Map scenario). The blue shaded area shows the cumulative emissions reduction that can be achieved in 2050 at different costs of emissions reduction. Measures are arrayed in order of increasing cost from left to right. Costs under the most optimistic technology assumptions are at the bottom of the blue shaded area and costs under the most pessimistic assumptions are at the top. CCS is in the mid-range of costs of all the measures needed to achieve the 48 GtCO_2 per year emissions reduction. Not only is CCS needed, but even more expensive measures will also be needed. This is the case regardless of whether optimistic or pessimistic technology assumptions are made.

Image Source: International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

CCS represents only a fraction of the total effort required to stabilize the climate. Efforts will also be required to develop and commercialize many of the other technologies needed to combat climate change, although CCS will be one of the more cost-effective measures. Advances in energy efficiency, renewable energy sources and other technology will all require extensive development. Investments in new and replacement infrastructure will be needed in every sector. IEA's Energy Technology Perspectives, 2008 study estimates that a total of US$45 trillion will be needed by 2050 to cut CO_2 emissions to half their 2005 levels. The predominant investment will be in the transportation sector due to the large projected expansion of that sector in developing countries.

Less investment is required in CCS to produce a gigatonne of emissions reduction than is required for some other necessary abatement options.

Table 2. Comparison of Global Emissions Reduction and Cost in 2050 with and without CCS

	BLUE Map Scenario	BLUE Map Scenario with no CCS
Emissions Reduction in 2050 (GtCO_2/yr)	48	41.6
2050 Emissions (GtCO_2/yr)*	14.0	20.4
Marginal cost to meet target (US$/tonne CO_2)	200	394

* These are the emissions at the BLUE Map scenario marginal cost of US$200/tonne CO_2. The 14 GtCO_2/yr target can only be met at the marginal cost of US$394/tonne CO_2 in the BLUE Map Scenario if there is no CCS. All costs are in constant 2007 US dollars.

Source: Table 2.5 of International Energy Agency, Energy Technology Perspectives, 2008: Scenarios and Strategies to 2050, OECD/IEA, Paris, June 2008.

As such, it is an efficient investment. A total of US$45.0 trillion is required between now and 2050 to combat climate change. Of that, US$3.0 trillion is required for CCS—US$1.4 trillion in power generation and US$1.6 trillion in industry/ fuel transformation. CCS represents just 6.7 percent of the global investment to reduce CO_2 emissions. Yet CCS will create 9.1 GtCO_2 per year of emissions reduction in 2050, which is 19.0 percent of the total global emissions reduction. This is shown in Table 3.

Understanding CCS Cost Estimates

Published estimates of CCS costs vary widely and are often difficult to reconcile. Cost estimates for technologies such as CCS, which are at an early phase of maturity, are more uncertain than for mature technologies. Estimates for CCS projects are usually based on hypothetical plants for which engineers and cost estimators have less experience than with comparable existing technologies. The cost of building a power plant with CCS, for example, is much more difficult to estimate than the cost of building a power plant without CCS. Plants with CCS have more options and there is a lack of experience building such plants. Much less is known about the ultimate plant design and project execution. As CCS matures, the uncertainty associated with cost estimates will decrease.

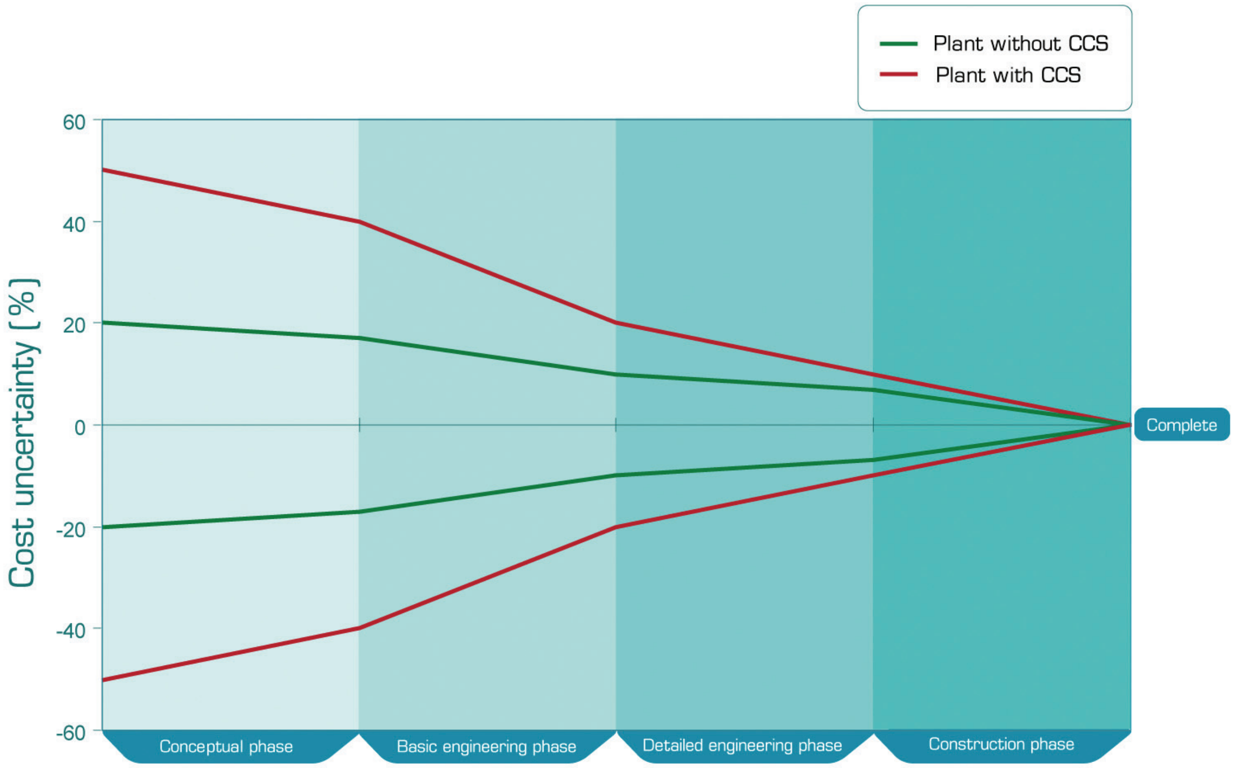
Accurate cost comparisons among technologies must also ensure that assumptions are consistent. For example, capital cost estimates may or may not include financing costs, which may be substantial. There are also regional differences, for example, in the cost of construction labor and commodities. Such assumptions may not always be explicitly stated.

These issues are not limited to CCS; they are typical of cost estimates of less mature technologies. These differences are compounded for a system as complex as CCS with the three very different stages of capture, transport and storage.

Table 3. Cutting CO_2 Emissions in Half: CCS Share of Investment and 2050 Emissions Reduction

Sector/Measure	Cumulative Investment (Trillion US$)	Share of Global Investment (%)	2050 Global Emissions Reduction (GtCO_2/Yr)	Share of Emissions Reduction (%)
Power Generation				
CCS	1.4	3.1	4.8	10.0
Other Power Generation Measures	2.2	4.9	13.5	28.1
Total	3.6	8.0	18.3	38.1
Industry/Fuel Transformation				
CCS	1.6	3.6	4.3	9.0
Increasing Efficiency/Fuel Switching	0.3	0.7	3.7	7.7
Total	1.9	4.2	8.0	16.7
Other Sectors				
All Measures	39.5	87.7	21.7	45.2
All Sectors				
CCS	3.0	6.7	9.1	19.0
Other Measures	42.0	93.3	38.9	81.0
Total	45.0	100.0	48.0	100.0

Source: Based on International Energy Agency, Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008. BLUE Map Scenario. Investment amounts are in constant 2007 US dollars.



Power plants with CCS have greater uncertainty in capital cost than plants without CCS at each phase of development. Most cost estimates of plant designs with CCS are conceptual in nature, whereas plant costs without CCS are based on experience. Uncertainty in capital cost goes to zero when a plant is built. The uncertainty bands shown in this graphic are illustrative and not indicative of any specific project.

Source: Bluewave Resources, LLC and CO2CRC.

The most widely-cited cost estimates for CCS with post-combustion capture in power generation tend to be extrapolations of the cost of the earliest option, amine separation. The original amine separation process, however, was not designed for CCS, but rather was adapted to CCS from other applications. Other options have now been proposed or are under development for CCS instead of amine separation. Some of these options have a good chance of improving on amine separation's cost and performance. Estimates based on amine separation or other early concepts may well overstate the cost of the post-combustion capture technology that will ultimately become commercial.

CCS Cost Trends

CCS costs are currently high due to the relatively early level of development, but are expected to come down as the technology matures. Cost uncertainty will also be reduced as experience is gained. Cost reduction is one of the primary goals of work on CCS, particularly for the capture stage. For example, the U.S. Department of Energy's goal is to develop CCS systems in which the cost of electricity generation would increase by less than 10 percent for pre-combustion capture and less than 35 percent for post-combustion capture. Similarly, the goal of the Castor project sponsored by the European

Commission is to reduce the cost of post-combustion capture from €50-60 down to €20-30 per tonne of CO_2.

Researchers are pursuing many options to reduce costs, including improvements to earlier concepts and new options for capture and storage. Much of the expected cost reduction will likely come not from the development of new technologies, but rather from a process of refinement and incremental improvement. CCS will be improved by building projects, learning what works well and what does not, identifying potential refinements, and making improvements to subsequent generations. This has been the experience with similar technologies.

Analogous technologies have experienced significant cost decreases as more were built, illustrated in Table 4. Capital and operating costs were reduced for these technologies as lessons learned in earlier installations were applied to later units, although sometimes after an initial increase. A doubling in production capacity reduced capital cost by 10 to 27 percent and the operating and maintenance costs by 6 to 27 percent.

CCS will also very likely experience such cost reduction. Much of the knowledge that will improve performance and reduce costs can only come from experience. The optimum design of components and the best way to integrate those components will be learned by building projects. The need for experience is a major reason why multiple commercial-scale demonstrations will be necessary to effectively bring costs down. Multiple projects will be required to address the diverse set of technologies and implement the lessons of learning-by-doing.

One current trend, however, is tending to increase the cost of CCS and its alternatives. Capital costs of major infrastructure projects throughout the world have been rising rapidly since about 2003, driven largely by increasing demand for construction materials in fast-growing developing countries such as China. This demand has affected the costs of proposed CCS projects as well as the costs of alternatives to CCS in power generation, such as renewables and nuclear energy.

Table 4. Cost Reductions Experienced by Technologies Similar to CCS

Technology	**Percent Cost Reduction for each Doubling of Technology Capacity**	
	Capital cost	Operating and Maintenance (O&M) Cost
Flue gas desulfurization	11	22
Selective catalytic reduction	12	13
Gas turbine combined cycle	10	6
Pulverized coal boilers	5	18
LNG production	14	12
Oxygen production	10	5
Hydrogen production	27	27

Source: Edward S. Rubin, Sonia Yeh, Matt Antes, Michael Berkenpas and John Davison, "Use of experience curves to estimate the future cost of power plants with CO_2 capture," International Journal of Greenhouse Gas Control, 1 (2007) 188–197, 26 February 2007.

Readiness of CCS

Given a substantial global commitment by government and industry, CCS can be ready in time to play a substantial role mitigating climate change. The first commercial CCS projects are now in operation in a few industrial facilities. CCS projects in the power sector will likely begin operation in the 2010s. Many will be demonstration projects. CCS can begin contributing a substantial portion of the required emissions reduction for power generation starting about 2020 and for more widespread industrial processes somewhat later. Like several other CO_2 reduction measures, transitional incentives will be required before CCS becomes commercially viable in most applications. Such incentives will no longer be required when the cost of CCS declines below the commercial value of CO_2 emissions reduction.

Many measures will be required to reduce CO_2 emissions. Some can start now; many others require new technologies not yet fully available, such as CCS. Those technologies can be developed.

As shown earlier, the potential "climate stabilization wedge" from CCS will grow to be large—9.1 $GtCO_2$ savings in 2050, which is about 19 percent of the emissions reduction needed in that year.

Given a strong commitment by government and industry to developing the technology and the institutional framework, CCS should be able to achieve those reductions**.** Power generation and other industrial sources constitute about 60 percent of CO_2 emissions produced by humans. Reducing these emissions is critical to achieving a stable climate.

Current Status of CCS Technology

The readiness of CCS is complex because CCS may be used for several types of CO_2 sources, each with different requirements. CCS is also a system that integrates three different and evolving stages (CO_2 capture, transport and geologic storage). Various technologies with different degrees of maturity compete for a role in each stage. Each of these technologies will be ready for different applications at different times.

Each of the stages of CCS is technically ready today for many applications. Existing technologies for those stages already work well in current applications. Each stage of CCS has been used commercially for many years, for some applications:

✓ Capture technologies have long been used commercially for high-concentration, high-pressure CO_2 sources. Over the last decade or so, as work on CCS has intensified, many new ideas for capture from lower-concentration, lower-pressure sources such as power plants have emerged. Technologies based on these ideas are at different levels of development. Some are still in the lab. For others, pilot plants have been operated and still others are ready for demonstration.

✓ CO_2 transport by pipeline, rail and truck has also long been safely used. CO_2 pipelines are in commercial use in several places. Ocean-going ships to transport CO_2 long distances have been proposed, but none have yet been built or operated.

- ✓ Geologic CO_2 storage has been conducted successfully in most types of reservoirs in which it is planned. More experience is needed to understand CO_2 behavior in diverse geologic formations, particularly deep saline formations and coal beds, and to refine methods to monitor and verify storage.

Success of the stages of CCS in their current applications, similarity of current to proposed applications, and the diverse technology options that are emerging, all give high confidence that CCS can be applied to more widespread sources such as power generation and types of storage reservoirs such as deep saline formations. Much

Current Commercial CCS Projects

Four fully-integrated, large scale CCS projects are in commercial operation today. Three—Sleipner, In Salah and Snøhvit—inject CO_2 from a natural gas production facility where it is separated from the natural gas sent to market. The fourth project captures CO_2 at the Great Plains Synfuels Plant and transports it to the Weyburn-Midale project. All four are contributing to the knowledge base needed for widespread CCS use.

Sleipner. The world's first commercial CCS project started in 1996 when Norway's state-owned oil company, Statoil, began injecting more than 1 million tonnes a year of CO_2 under the North Sea. This CO_2 was extracted with natural gas from the offshore Sleipner gas field. In order to avoid a government-imposed carbon tax equivalent to about US$50/tonne, Statoil built a special offshore platform to separate CO_2 from other gases. The CO_2 is re-injected about 1,000 meters below the sea floor into the Utsira saline formation located near the natural gas field. The formation is estimated to have a capacity of about 600 billion tonnes of CO_2, and is expected to continue receiving CO_2 long after natural gas extraction at Sleipner has ended.

In Salah. In August 2004, Sonatrach, the Algerian national oil and gas company, with partners BP and Statoil, began injecting about 1 million tonnes per year of CO_2 into the Krechba geologic formation near their natural gas extraction site in the Sahara desert. The Krechba formation lies 1,800 meters below ground and is expected to receive 17 million tonnes of CO_2 over the life of the project.

Snøhvit. Europe's first liquefied natural gas (LNG) plant also captures CO_2 for injection and storage. Statoil extracts natural gas and CO_2 from the offshore Snøhvit gas field in the Barents Sea. It pipes the mixture 160 kilometers to shore for processing at its LNG plant near Hammerfest, Europe's northernmost town. Separating the CO_2 is necessary to produce LNG and the Snøhvit project captures about 700,000 tonnes a year of CO_2. Starting in 2008, the captured CO_2 is piped back to the offshore platform and injected in the Tubåsen sandstone formation 2,600 meters under the seabed and below the geologic formation from which natural gas is produced.

Weyburn-Midale. About 2.8 million tonnes per year of CO_2 is captured at the Great Plains Synfuels Plant in the U.S. State of North Dakota, a coal gasification plant that produces synthetic natural gas and various chemicals. The CO_2 is transported by pipeline 320 km (200 miles) across the international border into Saskatchewan, Canada and injected into depleting oil fields where it is used for EOR. Although it is a commercial project, researchers from around the world have been monitoring the injected CO_2. The IEA Greenhouse Gas R&D Programme's Weyburn-Midale CO_2 Monitoring and Storage Project was the first project to scientifically study and monitor the underground behavior of CO_2. Canada's Petroleum Technologies Research Centre manages the monitoring effort. This effort is now in the second and final phase (2007-2011), to build the necessary framework to encourage global implementation of CO_2 geological storage. The project will produce a best-practices manual for carbon injection and storage.

work, however, remains to refine the technologies, reduce costs, select the best technologies and designs, and integrate all of the stages.

CCS and its stages are commercially viable today in several applications. CCS as an entire system is commercially viable in some projects. Individual stages are commercially viable on their own in some applications. The capture stage is commercially viable where capture costs are low due to high concentrations of CO_2 at high pressure or where a valuable end-product is produced after separation. The transport stage is commercially viable where CO_2 has an adequately high value at a distance from the source, typically for Enhanced Oil Recovery (EOR). The storage stage is commercially viable where CO_2 is injected into depleting oil fields for EOR. Most of the CO_2 for EOR is now extracted from natural underground formations. Ironically, CO_2 is in short supply and is considered highly valuable today in some of the oilfields where it could most be used.

Phases of Technology Development

Large-scale, complex technologies such as capture or geologic storage require extensive development over a period of time. This development typically proceeds in several phases. Each phase increases in scale, complexity and cost and each builds upon what was learned in the prior stages. New ideas are first tried out in research and development programs, typically in laboratories or small-scale experiments. Technologies that prove successful in the lab may move on to pilot projects. These are facilities that do everything a full-scale, commercial installation would, but on a smaller scale and at a lower total cost. The demonstration phase of a new technology involves the operation of a full-scale facility that may still have many experimental aspects. Everything that is learned up to this point then goes into the first commercial projects, which is sometimes called the deployment phase. These early projects are often not fully commercially viable but form the basis for more efficient, effective and less-costly commercial phase projects.

In practice, these phases are not always distinct; projects may combine attributes of multiple stages. Various CCS technologies are currently in each development phase.

CCS is not yet widely commercially viable as an integrated system in the applications where its use could be most widespread. These applications include power generation and many industrial processes. The question is: what will it take to make CCS commercially viable?

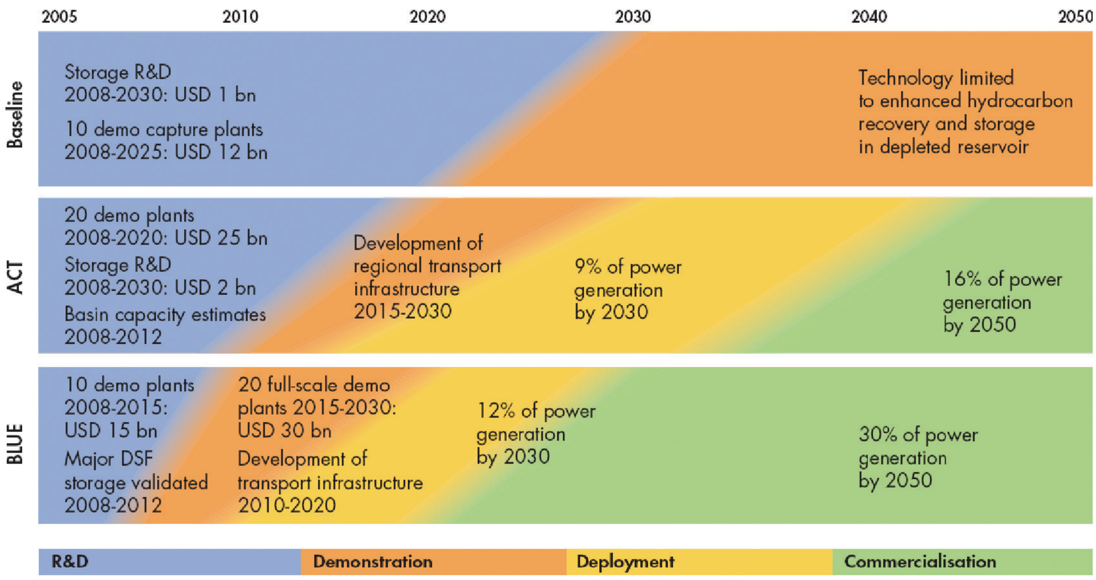
Making CCS Technically Ready and Commercially Viable

The speed with which CCS technology becomes technically ready and commercially viable in widespread applications will depend, in large part, on the resources devoted to developing it. As discussed earlier, the IEA Energy Technology Perspectives, 2008 study evaluated what it would take to make the full set of required technologies commercial on a timely basis to create necessary emissions reductions. Timelines to bring technologies into commercial use in each of the scenarios (Baseline, ACT Map, BLUE Map) were developed for each new technology, including CCS. The following page contains timelines for CCS in the power sector and the technology targets required to achieve those timelines. The timelines show how CCS can be moved through the phases of development (research and development, demonstration, deployment and commercialization) to achieve the scenario goals. Each path corresponds to a different level of global commitment to reach the technology targets.

A fundamental conclusion of the Energy Technology Perspectives, 2008 study is that cutting emissions in half will require substantial efforts to develop and commercialize a wide range of technologies not available today. CCS for both power generation and industry is a vital part of that portfolio of technologies.

Other studies and roadmaps in Australia, Canada, China, Europe and the United States and by the CSLF confirm that, with adequate effort, CCS can be commercial by about 2020. While much needs to be done to develop and deploy

Technology timeline



In this roadmap, commercialisation assumes an incentive of USD 50/t CO_2 saved.

Technology targets

	ACT: Emissions Stabilisation	BLUE: 50% Emissions Reduction
RD&D		
Capture technologies for three main options (post-combustion, pre-combustion, and oxy-fuelling)	Technologies tested in small- and large-scale plants. Cost of CO_2 avoided around USD 50/t by 2020. Chemical looping tested	
Demonstration targets	20 large-scale demo plants with a range of CCS options, including fuel type (coal/gas/biomass) by 2020	30 large-scale demo plants with a range of CCS options, including fuel type (coal/gas/biomass) by 2020
New gas-separation technologies: membranes & solid adsorption	New capture concepts: next-generation processes, such as membranes, solid absorbers and new thermal processes	
Technology transfer	Technology transfer to China and India	Technology transfer to all transition and developing countries
Deployment		
Regional pipeline infrastructure for CO_2 transport	Major transportation pipeline networks developed and CO_2 maritime shipping	
Deployment targets	Early commercial large-scale plants by 2015 (ZEP, ZeroGen, GreenGen)	30% of electricity generated from CCS power plant by 2050

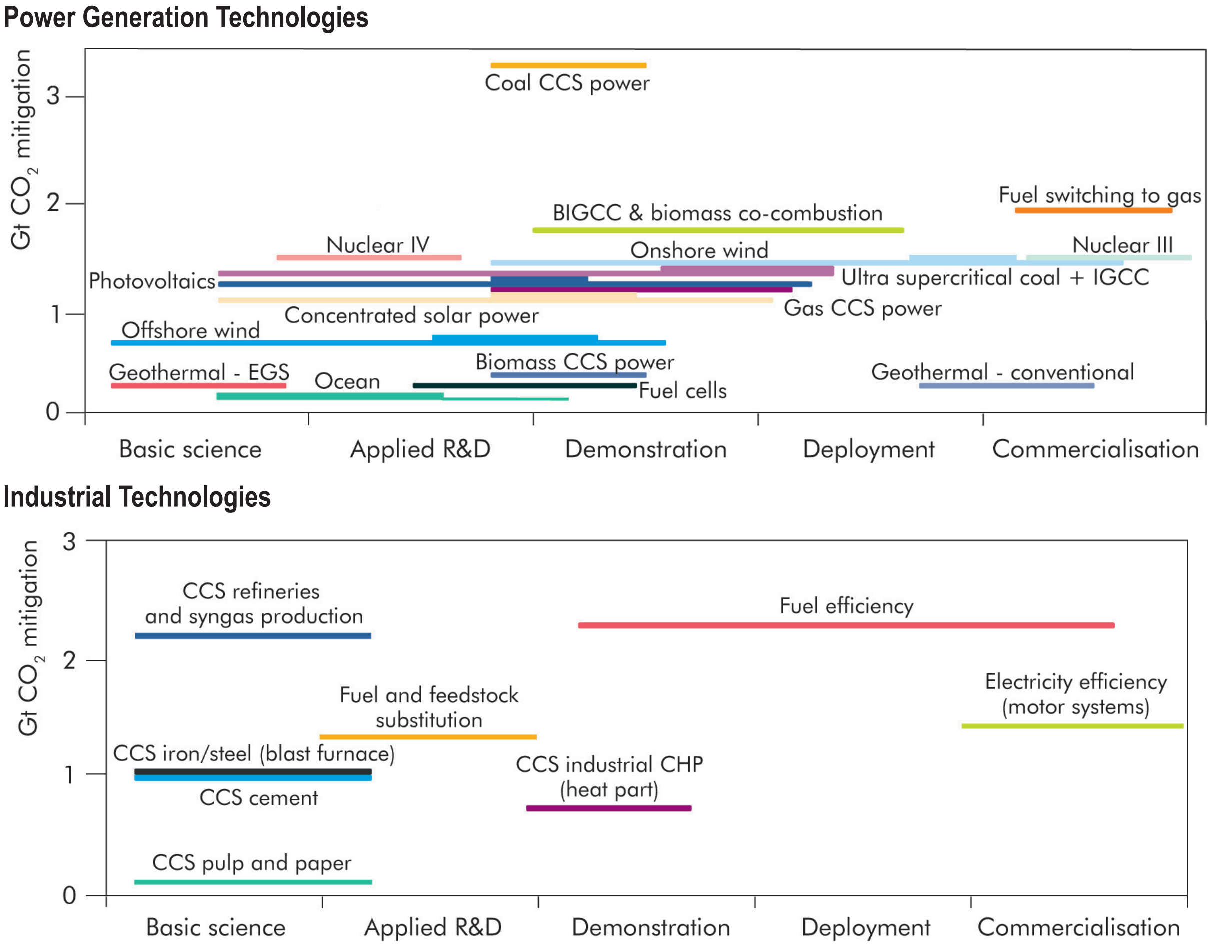
Technology timelines for CCS vary in the three IEA scenarios. Widespread commercial use of CCS for power generation is possible by about 2020, but this will require a substantial effort to advance the technology development and the operation of multiple demonstration projects.

Image Source: International Energy Agency, Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050, OECD/IEA, Paris, June 2008.

commercial CCS, it can be done. It requires mostly evolutionary progress and integration of existing technologies, not the development of entirely new ones. This is a lesser challenge than developing new technologies and there are many options.

CCS Readiness Compared to Other Measures

The question of readiness is important and needs to be asked of <u>all</u> greenhouse gas mitigation measures under development. While CCS requires further development for many applications, many of the other technologies being considered to help reduce CO_2 emissions also require further development, often extensive. The commercial use of many of the other technologies proposed to mitigate CCS is probably further away and far more uncertain than CCS. (See figure below.) Given the inherent uncertainty of technology research and development, pursuing a broad and diverse portfolio of technology options is the approach with the highest likelihood of success in achieving adequate emissions reduction. CCS is one of the least uncertain options in the portfolio of new CO_2 emissions reduction technologies. This is especially true because each stage of CCS is really a family of many different technologies, each of which is advancing. CCS has many chances to succeed.



This figure compares the development status of CCS and other new emissions reduction technologies in the power generation and industrial sectors. It also shows each measure's potential for CO_2 mitigation. In both sectors, CCS has the greatest mitigation potential. In the power sector, CCS is more advanced in development than many other options. In the industrial sector, fuel and electricity efficiency can reduce CO_2 emissions earlier, but CCS can eventually mitigate more CO_2 emissions. These technologies all require further development.

Image Source: International Energy Agency, <u>Energy Technology Perspectives, 2008, Strategies and Scenarios to 2050</u>, OECD/IEA, Paris, June 2008.

While many emissions reduction technologies may not be ready today, they are all still vitally needed to reduce CO_2 emissions adequately. The IEA Energy Technology Perspectives, 2008 study makes it clear that, while substantial emissions reduction must start soon with technologies currently at hand, today's technologies are not sufficient. New technologies, some of which will not be available for many years, are needed. Given its large potential for emissions reduction, CCS is probably the most important of these.

Capture-Ready Plants and Retrofits

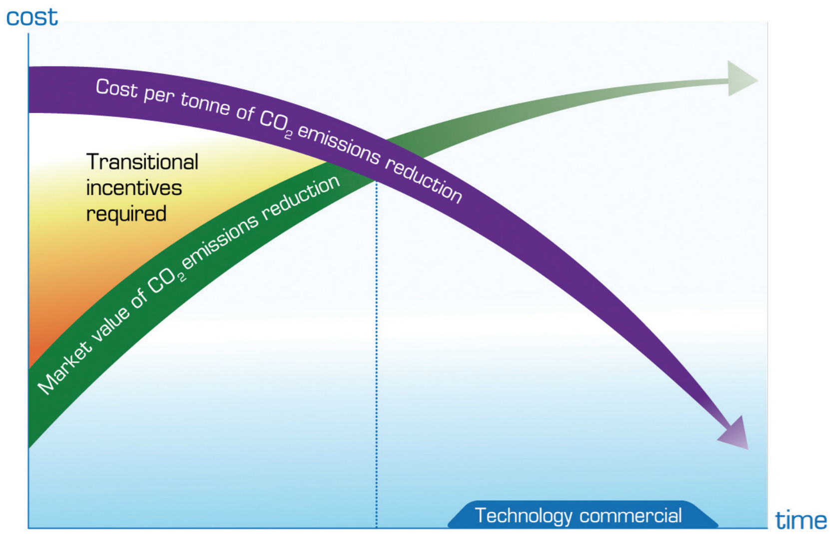
Many new large coal and natural gas power plants will be built to meet expected needs for electricity over the next decade or so before CCS is expected to be commercially viable for most power generation. A concept called "capture readiness" has been proposed for power plants built before CCS is fully commercial. A capture-ready plant would not initially have the capability to capture CO_2 but could be modified later to implement CCS when it is commercially viable. The design of a capture-ready power plant would depend on the plant and the type of capture. In general, capture readiness would require a location economically accessible to geologic storage with adequate capacity, space for the capture and compression equipment and the ability to integrate control systems.

This concept has generated considerable discussion as a measure to avoid "locking in" the emissions of power plants built before CCS is commercial for that application. From the perspective of a power plant developer, capture readiness would avoid plants being rendered obsolete by future CO_2 emissions limitations. First proposed for power plants in developing countries, it is also now being discussed for industrialized countries.

No definition of capture-ready plants is universally accepted. Perhaps the most widely-cited definition is that developed by the IEA Greenhouse Gas R&D Programme (IEAGHG):

> *A CO_2 capture-ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture ready is to avoid the risk of "stranded assets" or "carbon lock in."*
>
> *Developers of capture-ready plants should take responsibility for ensuring that all known factors in their control that would prevent installation and operation of CO_2 capture have been eliminated. These might include:*
>
> - *A study of options for CO_2 capture retrofit and potential pre-investments*
> - *Inclusion of sufficient space and access for the additional plant that would be required*
> - *Identification of a reasonable route to CO_2 storage*
>
> *Competent authorities involved in permitting power plants should be provided with sufficient information to judge whether the developer has met these criteria.*

This is a very broad definition, offered as a starting point for discussion. Over time, more specific definitions and regulatory requirements will likely emerge. Various proposals have been made for capture-ready power plants. The European Commission (EC), for example, has proposed that all new fossil power plants be capture ready, based on the IEAGHG definition. The United Kingdom is developing the details for its implementation of the EC proposal. Elsewhere, developers claim that their proposed power plants are capture ready. Ultimately, clear legislation or regulation based on adequate technical data must provide the definition of capture ready and its significance.



Like other emissions reduction measures, transitional incentives will be required before CCS becomes commercially viable in applications such as power generation. Such incentives will no longer be required when the cost of CCS declines below the value of CO_2 emissions reduction.

Image Source: Bluewave Resources, LLC and CO2CRC.

Retrofitting existing power plants would face many of the same issues as capture-ready plants. There is much less flexibility with retrofitting. Decisions on factors that determine feasibility of capture have already been made. Nonetheless, studies show that some existing power plants might be able to add CCS, provided they are relatively new and efficient, have adequate space, and are located directly above or very near to potential injection sites. Several pilot projects and major demonstration projects are planned as retrofits. Another option with older, inefficient plants might be to both replace the existing power generation equipment and add CCS. Retrofitting will be very site specific.

Time Frame for Commercial Viability of CCS

The economic value of CCS will be determined primarily by the value that society—through government—places on reducing CO_2 emissions. That value could be an explicit monetary value created through a carbon trading system or carbon taxes; it could be implicit through regulatory limitations on emissions from specific facilities; it could be mandated use or a portfolio standard; or it could be a combination of approaches. Different approaches are being considered in different places. Examples include the Norwegian offshore carbon tax, the European Trading System for CO_2, and the Kyoto Protocol's Clean Development Mechanism (which does not yet apply to CCS).

Implementation of long-term incentives is at an early phase. Probably the most common incentive is a "cap-and-trade" emissions trading system for CO_2. Under such a system, tradable "emission allowances" are allocated within a defined market up to a limit or "cap." This limit decreases over the years in most proposals. A market is created in CO_2 emissions which sets a monetary value for CO_2 emissions reduction. Its value depends on the overall supply and demand of emission allowances. Emission trading systems have already been established in the European Union, the Canadian province of Alberta, and the Australian state of New South Wales. National trading systems have also been proposed by the Australian and Canadian governments. In the United States, there is a voluntary CO_2 trading market; several states are working on trading systems; and proposals have been made in Congress for a national cap-and-trade system.

At current or projected emissions allowance prices in existing trading systems, such as the European Trading System (ETS), CCS would not be commercially viable over the next decade for power generation, its most widespread application. Even though the technology is technically ready for use, its cost is higher than the ETS price and there are too many uncertainties for most firms to use the technology, unless transitional incentives are employed. While a few—mostly very large—industrial firms may be early movers (see box), the vast majority of firms are likely to wait until the cost and uncertainties come down, unless substantial offsetting incentives are provided. Even early movers will not proceed with projects that are not expected to be commercially viable.

Transitional incentives will be required for demonstration and early commercial CCS projects before projects become commercially viable. Such transitional incentives may include government cost-sharing on demonstration projects, portfolio generation standards, public investment, trust funds or various types of tax incentives such as investment tax credits. Similar transitional incentives are already widely used to advance emissions

Why Be an Early Mover on CCS?

Several power companies are deeply involved with CCS research and are implementing CCS at their power plants, long before it is required or economically viable. Why would they do that? They say that it is to gain experience to put them ahead of the game when the time comes.

Duke Energy, a large U.S. power generator, is planning an IGCC power plant at Edwardsport, Indiana at a cost of US$2 billion, considerably more than a conventional coal-burning power plant with the same capacity. "Duke believes IGCC and carbon capture and storage technology offer great promise in allowing us to continue using abundant, affordable coal in a world in which greenhouse gas emissions will be regulated," said John Stowell, Duke's vice president of environmental health and safety policy. "We are confident that the technology will work at commercial scale. Our Midwest power plants are located on favorable geologic ground where we have a real chance to prove and improve the technology," Stowell added.

Global diversified mining company Rio Tinto and the global energy company BP have formed a joint venture company called Hydrogen Energy to develop and operate low emissions power projects utilizing fossil fuels and CCS. Hydrogen Energy is developing two projects, one in California and one in Abu Dhabi. Both are progressing through feasibility studies with an objective of starting operation in the early to mid 2010s. Rio Tinto believes that CCS will make an important contribution to reducing emissions of greenhouse gases to the atmosphere. "The investment we are making in Hydrogen Energy will allow us to deliver decarbonised energy and carbon capture and storage.... Investing now means we will be well-placed to create value for shareholders from opportunities in the emerging clean power market," said Tom Albanese, CEO of Rio Tinto.

Another large U.S. power company, American Electric Power (AEP), is moving down all three capture paths—post-combustion, pre-combustion and oxyfiring—simultaneously. In addition to the post-combustion retrofits, AEP plans to build IGCC units in two U.S. states, West Virginia and Ohio. AEP is also working on a feasibility study on oxy-coal carbon capture and expects to have a commercial-scale installation of the technology on an AEP plant in the 2012 to 2015 timeframe. "Technology development needs are often cited as an excuse for inaction, but we see these needs as an opportunity for action," Nick Akins, AEP executive vice president, said.

The European electric utility Vattenfall is conducting several major CCS projects. These projects include an oxyfiring pilot plant now in operation at its Schwarze Pumpe plant, storage of the CO_2 captured at Schwartze Pumpe in the Altmark gas field, capture of CO_2 at its Nordjylland power plant in Denmark and participation in the European Test Centre Mongstad. According to Lars G. Josefsson, CEO of Vattenfall, "Alternative sources of energy are developing rapidly; nevertheless, the world will remain dependent on fossil fuels for a long time and CCS is an essential part of the solution. Vattenfall has taken a leading position in this field to get a first-mover advantage in the market. It is not only necessary from a climate perspective; it is good business, too."

reduction measures such as renewables and efficiency and, in some cases, for CCS projects. Transitional incentives are needed before, but not after, the value of emissions reduction exceeds the market value. As CCS develops, the costs and risks go down and, as emissions caps tighten, the value of such reductions increases, thus making transitional incentives unnecessary.

The economic value of CCS will also be determined, in part, by how level the incentives playing field is for CCS compared to other emissions reduction measures. A level playing field exists when the incentives—both transitional and permanent—are essentially the same for any measure of the same effectiveness. A playing field that is not level can result in the use of less cost-effective technologies to reduce CO_2 emissions.

With an adequate global commitment by government and industry, CCS can be ready to make a timely contribution to mitigating climate change. By about 2020, CCS can begin to contribute significantly to emissions reduction for power generation. Somewhat after 2020, CCS can begin to contribute to emissions reduction in widespread industrial processes.

What It Will Take

In order for CCS to enter timely, widespread commercial use, the capture and geologic storage stages of CCS require further technical development, as does the integration of the capture stage with host facilities. More experience in larger and more diverse projects is also necessary. Progress is being made in all these areas, but more work is required. Much of that work is ongoing.

Commercial CCS also requires the creation of enabling institutional frameworks that consist of:

- Effective expertise and institutions,
- Viable legal-regulatory frameworks,
- The ability to finance CCS, and
- Public understanding and support for CCS.

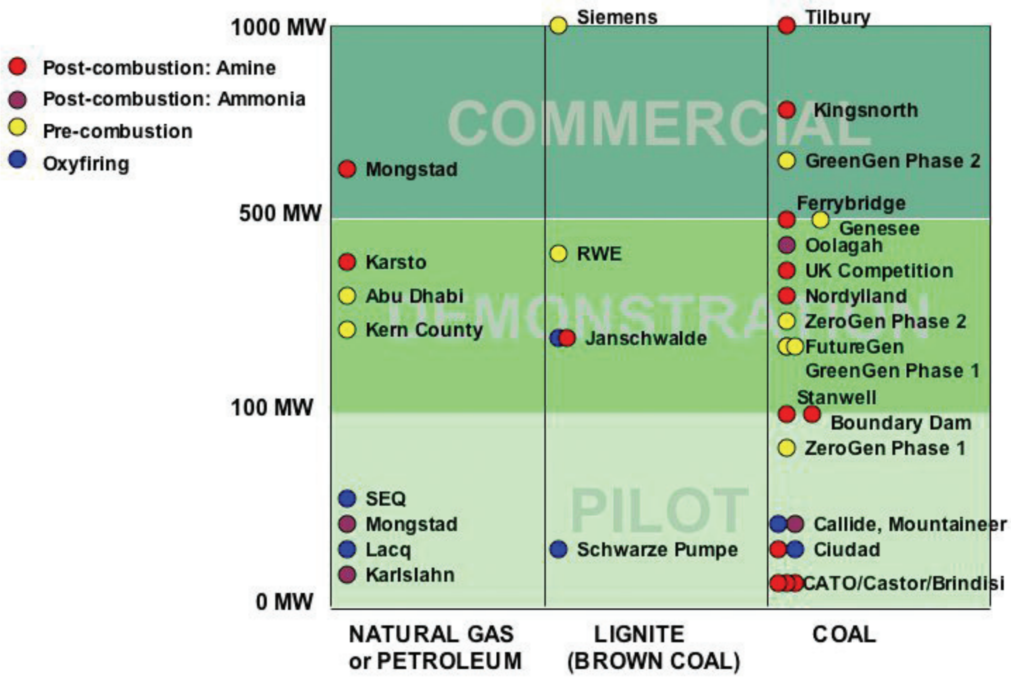
Developing the Technology

The major challenge associated with capture is its high cost for low-concentration, low-pressure, high-volume sources such as power plants. For power generation, three alternative approaches to capture—pre-combustion, post-combustion, and oxyfiring—are being developed. The objective of much of the work on each of these approaches is to substantially reduce cost. Each approach has strong advocates in the scientific and engineering community. It is not clear which approach will ultimately prove most cost-effective. It is still early in the development of CCS; much more work needs to be done; and new and innovative ideas are continuing to emerge. It is possible that different approaches may prove most attractive under different circumstances. Capture technologies for industrial processes such as steel and cement making must be specifically designed for those types of facilities.

Widespread implementation of geologic storage requires a more complete understanding of what happens to the CO_2 when large volumes of CO_2 are injected under diverse geologic conditions. A better understanding will facilitate development of storage practices tailored to a wide variety of geological conditions. Experience so far has been in a limited number of geologic settings.

CCS technologies must also be integrated with host facilities and experience must be gained building and operating these technologies on a larger scale. The Annex "Advancing CCS Technology" explains CCS technology in greater detail and describes some of the projects underway to develop that technology further.

Rapid progress is improving effectiveness, efficiency and cost, as well as applicability to different emission sources and geologic formations. Advances in capture technologies are continuing to take place as work proceeds. As further CCS experience is gained, more will be learned about how to implement CCS projects, and the cost and technical barriers will fall. More advanced and effective options for capture will become available over time. Similarly, testing of CO_2 storage in different geologic formations is building the knowledge required to store CO_2 in the wide range of geological conditions that will eventually be needed. Chemical and geologic engineering have a long history of advancement through refinement and incremental improvement. Such refinements and improvements will also



Many new capture projects for power generation are now planned throughout the world. They will use various fuels and capture technologies and are different sizes. A sample of the proposed projects is illustrated here. If a diverse set of these projects is ultimately implemented, they will provide much of the information necessary to make CCS widely commercially viable.

Image Source: Adapted from IEA Greenhouse Gas R&D Programme.

occur with CCS. Numerous projects are underway throughout the world. Progress to date has been substantial and more can be expected.

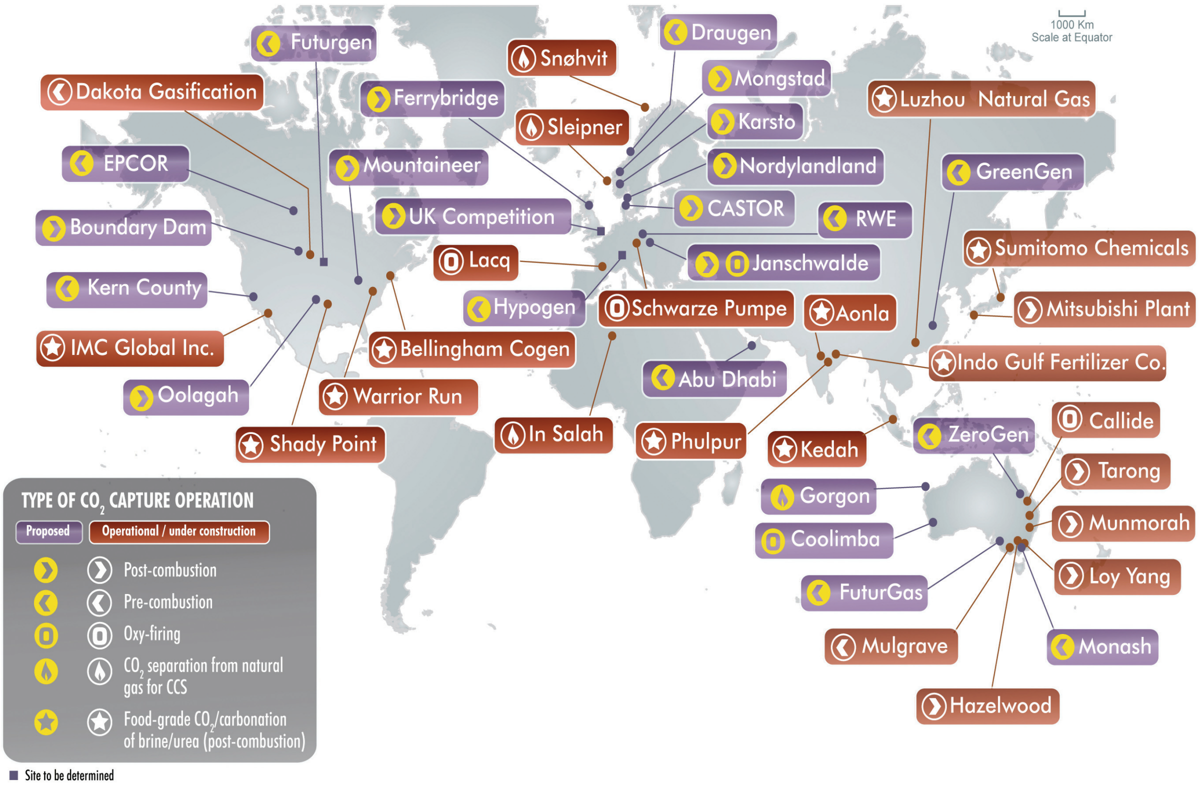
The challenges of integration and scale can be met through the experience of building and operating fully-integrated and commercial-scale CCS facilities. Many projects are in the pilot, demonstration and early commercial phases. Ultimately, not all will enter operation, but timely implementation of CCS will require that many of these projects succeed. Over the coming years, many commercial-scale fully-integrated projects will likely be built. Ideally, such facilities will be phased in different generations so that the lessons learned in one generation can be built into the next.

Considerable work on CCS is being conducted throughout the world and these efforts are growing rapidly. Many scientists, engineers and geologists are now devoting their efforts to all aspects of CCS. The number of these professionals is growing rapidly along with CCS-related budgets and the number of projects in both the public and private sectors.

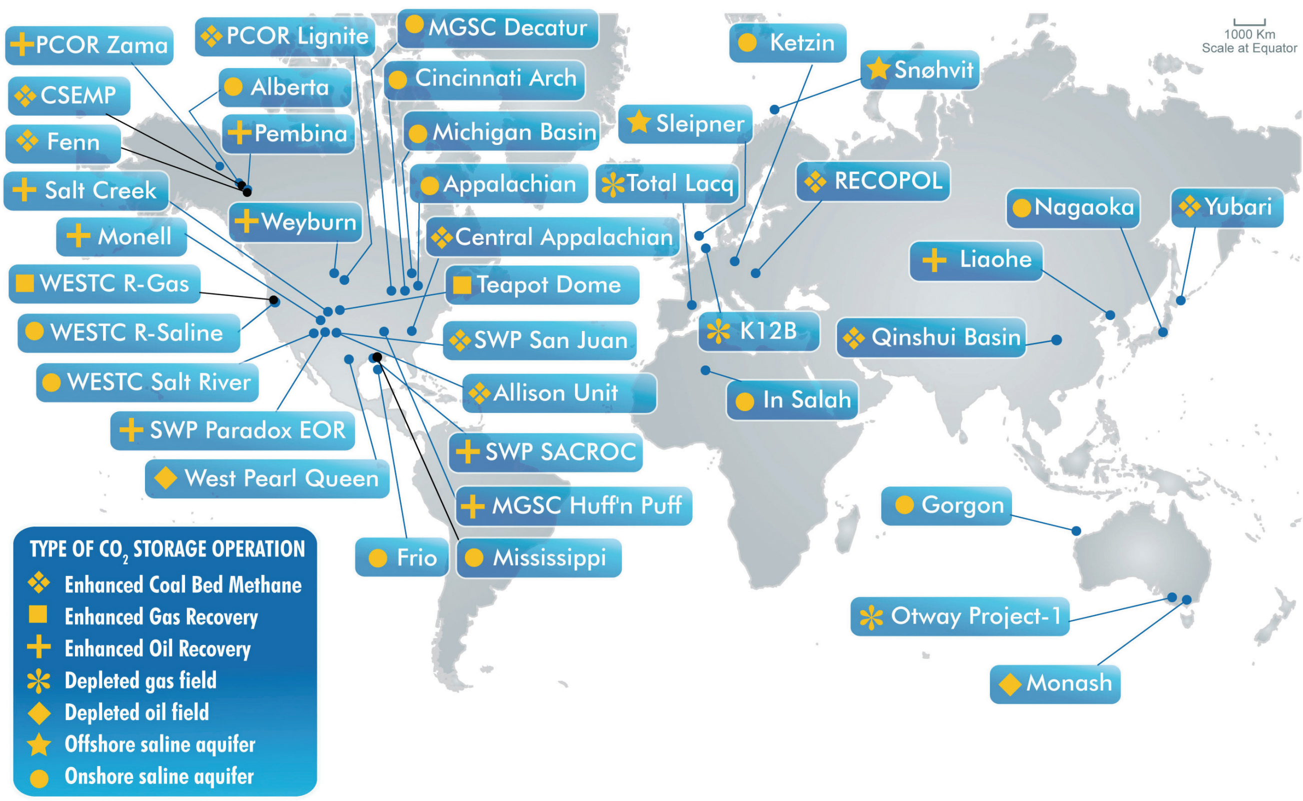
Government budgets devoted to CCS have been expanding rapidly from virtually nothing in the late 1990s, and the priority of CCS is rising. The U.S. Department of Energy's fiscal year 2008 CCS budget is US$283 million across several programs and is growing from year to year. In addition, US$6 billion in loan guarantees and US$1.65 billion in tax credits are targeted at CCS projects. The European Commission (EC) is spending approximately €32 million per year on CCS and several of its member states also have significant and growing budgets for CCS. The 2008 Canadian federal budget for CCS is C$250 million and provinces also contribute funding. The Canadian province of Alberta alone is planning to spend C$2 billion on new CCS projects. The Australian government has established its low-emissions coal initiative with funding of AU$500 million and has announced an international carbon capture institute funded at AU$100 million. Together, these and other countries are funding a diverse array of projects on every aspect of CCS and this funding is expected to grow. In addition, international collaboration among governments is taking place through the International Energy Agency (IEA) and the Carbon Sequestration Leadership Forum (CSLF), with 21 countries and the European Commission as members.

Private-sector investments in all aspects of CCS technology have also rapidly increased as equipment vendors and service providers seek a posi-

Capture Projects



Storage Projects



Increasing numbers of projects on all aspects of CCS are taking place throughout the world. As time goes on these projects are becoming more advanced and are moving toward commercial status.

Image Source: CO2CRC.

tion in what they see as a potentially large and fast-growing market and as the owners of large sources of CO_2 seek ways to reduce their emissions. Many companies are making investments.

Private collaborations are also taking place through various joint ventures and through joint projects such as the Carbon Capture Project, sponsored by eight of the world's leading energy companies and the EC's Zero Emissions Platform, comprised of over 30 companies, NGOs and other organizations. In the United States and parts of Canada, private companies and NGOs participate in seven Regional Carbon Sequestration Partnerships sponsored by the U.S. Department of Energy. These Partnerships are undertaking numerous projects, particularly in testing geologic storage in diverse geologic settings. The Australian Coal Association has established a voluntary fund that will raise AU$1 billion for low-emissions and demonstration projects over a ten-year period.

Building Expertise and Institutions

CCS projects must be planned, built, operated and closed, and all phases must be subject to appropriate regulation. Most private companies and government agencies that will conduct each of these functions have yet to fully develop the necessary capabilities and expertise. The people who are currently involved in CCS are, for the most part, experts who are involved in research and development activities.

Building the expertise and institutions will require the development of educational programs in universities and other training programs. Today, few such university courses or training programs exist, but they are beginning to emerge. One ex-

Career Opportunities in CCS

Consider a career in CCS. That is the advice from Dutch graduate student Michiel C. Carbo. Carbo is a Ph.D. candidate in the field of zero emissions power plants and works at the Energy Centre of the Netherlands (ECN). He is preparing for a career in CCS, an industry now in its infancy, but with tremendous growth potential.

Carbo was attracted to carbon mitigation and CCS not only because "it's a good cause," but because he finds CCS very challenging. "There are a lot of ins and outs and it is cutting edge research," he said. Carbo plans to earn his Ph.D. in chemical engineering in 2009 to prepare him to work on CCS. Toward that end, he also attended the first CCS Summer School of the International Energy Agency's Greenhouse Gas R&D Programme (IEAGHG). At the moment, very few specific academic courses are available for those looking to enter the new field of CCS, so IEAGHG attempts to fill the gap.

Since the field is young and research has only started in earnest relatively recently, "a lot of the studies involve learning-by-doing," he said. Chemical engineers like Carbo generally work on CO_2 capture. They look for ways to reduce costs and energy requirements. Those chemical engineers need to keep abreast of the work being done by geologists at the other end of the CCS process. Geologists are continually trying to improve CO_2 injection and storage. Both disciplines work to improve efficiencies and lower costs. In the Netherlands, the two disciplines work together at CACO, the Dutch national CCS program. Similar programs around the world unite disciplines to work on CCS.

Carbo sees interest in CCS growing rapidly. "There are more and more attendees [at conferences] and more and more publications as well," says Carbo. Many engineers working in CCS are employed by research institutions. As CCS takes off, enormous additional opportunities await engineers with the right skills and knowledge.

ample is a summer course on CCS operated by the IEA Greenhouse Gas R&D Programme. Both the CSLF and Asia Pacific Economic Cooperation (APEC) have CCS capacity-building initiatives that conduct training for developing countries.

Increasing numbers of organizations are now working on various aspects of CCS. Expertise and institutions will be built as private firms, governments, and research institutions engage in activities to develop and implement CCS, and as educational institutions and others begin to teach about CCS.

Creating Legal-Regulatory Frameworks

CCS is a new type of activity and complete legal-regulatory frameworks for CCS do not yet exist in most jurisdictions. Many legal-regulatory issues must be addressed: permitting, property rights, long-term liability, monitoring requirements, the classification of CO_2, and jurisdictional issues, to name a few.

Legal-regulatory frameworks are being created in many countries. In Australia, the federal government has proposed a framework for CCS regulation using the Offshore Petroleum Act of 2006 as a template. In Canada, legal frameworks that will apply to CCS are being created at both the federal and provincial level. On the Canadian federal level, proposed greenhouse gas emissions reduction targets are to be set by the Regulatory Framework for Industrial Greenhouse Gases, which is to go into effect in 2010. Under this Framework, new oil sands and coal-fired electricity plants entering operation in 2012 and later will have to meet a plant standard equivalent to CCS. Other regulatory activities are taking place at the provincial level, particularly in Alberta, the center of the Canadian energy industry. The EC in early 2008 proposed a directive to enable environmentally-safe capture and geologic storage of CO_2 as part of a major legislative package. In this package, the EC has proposed that all new fossil fuel plants be capture ready. In the United States, the existing framework of federal and state laws in areas such as oil and gas and underground injection is being adapted to CCS. The U.S. Environmental Protection Agency is proposing rules for underground injection of CO_2. Japan is developing a system of permits for sub-seabed storage. Injection under the seabed is covered by the London Convention and its 1996 Protocol, which were amended in 2007 to allow injection of CO_2 in sub-seabed geologic formations. The IEA has recently started a CCS Regulators' Network in which regulators from around the world can share their ideas and experiences.

One particularly important legal issue is financial responsibility for the long-term safety and reliability of geologic storage. The injection phase of geologic storage for a specific project will typically take place over 20 to 40 years. Injected CO_2 must stay in the ground for much longer, perhaps thousands of years. This is longer than the life span of any project and longer than commercial organizations last.

Project developers seek specific, well-defined limits on liability. Similarly, the public also seeks an understanding of risks and assurances that those conducting geologic storage take appropriate responsibility for the consequences of their actions.

Financing CCS

Ultimately, CCS projects will be financed entirely on a commercial basis. Commercial financing will depend on adequate returns on CCS investments and appropriate risk-sharing. Currently-commercial, large-scale projects (Sleipner, In Salah, and Snøhvit) were financed on the balance sheets of large multinational firms and are part of much larger portfolios and corporate strategies. In the case of Sleipner and Snøhvit, CCS had high value as a means of avoiding a carbon tax. Eventually, CCS will need to create economic value on a stand-alone or retrofit basis for more firms' power or industrial facilities. As the price of CO_2 emissions rises and costs and risks decrease, more commercial financing will become available. Until then, CCS projects will require public financing for some share of capital costs. In addition, CCS will raise the operating cost for facilities. Commercial viability will require offsetting higher operating costs by giving value to CO_2 reduction.

Major projects are now being developed largely through various forms of public-private partnerships in which government and industry share costs and risks. Examples of such partnerships include the Cooperative Research Centre for Greenhouse Technologies (CO2CRC) in Australia, the ecoENERGY Technology Initiative in Canada, the Regional Carbon Sequestration Partnerships in the United States and Canada, the EC's Zero Emissions Platform and the CCS Demonstration Competition in the United Kingdom. The goals of these partnerships are often ambitious. For example, the goal of the ZEP is to enable European fossil fuel power plants to have zero CO_2 emissions by 2020.

CCS will not be a stand-alone technology. It will be part of larger projects that are the sources of the CO_2 that CCS abates. Those projects will have their own goals, for example, the production of electricity, natural gas, steel or cement. CCS will be commercially viable and financeable for its CO_2 source when the value of CCS exceeds its cost. CCS will be evaluated by potential users on the basis of how it affects total project economic performance, not just the costs of the CCS component. For example, CCS operating costs could affect how much electricity a power plant could economically generate within its electric system. Integration with the source facility is critical.

Project developers also need to understand the potential liabilities they face and ensure that those risks are acceptable to investors. Various methods of allocating risk and balancing these interests have been proposed, including private insurance, government assumption of long-term liabilities and various types of funds paid for by the operators. Discussions are underway about how to provide for liability sharing; it will eventually be the topic of legislation or regulation in many jurisdictions. Knowledge of geology and storage engineering developed over the next several years through geologic storage projects is fundamental. Early projects may require greater public assumptions of financial liability. As the risks of CCS are defined and reduced, it can be expected that treatment of financial liabilities will eventually follow normal commercial practices.

Public Understanding

Implementation of CCS will require public understanding and support. The public must understand why CCS is needed to mitigate climate change, how it will be conducted, why it will be safe and its role in the overall portfolio of climate mitigating measures. Surveys indicate that the public in most countries is generally unaware—or only recently becoming aware—of CCS. Efforts are underway in many countries to raise public understanding of CCS.

Expert Recommendations

At their 2005 Summit in Gleneagles, Scotland, the G8 Heads of State requested that the IEA and CSLF consider a number of issues relating to CCS, including how to accelerate near-term opportunities for CCS. In 2006 and 2007, the IEA and CSLF convened leading experts on CCS from around the world in a series of workshops to discuss near-term opportunities for CCS. These experts discussed the barriers to widespread commercial use of CCS and developed 27 recommendations to advance near-term deployment of CCS.[2] The recommendations addressed both technical and institutional issues. To a large extent, these recommendations lay out what would be required to make CCS both technically ready and broadly commercially viable by about 2020. They were delivered to the G8 at its 2008 meetings in Japan. Some of the most important of these recommendations are listed below.

Recommendations Addressing Technical Issues

- Demonstrate CO_2 capture and storage through a diverse portfolio of least 20 fully integrated industrial-scale CCS demonstration projects;
- Undertake and fund work projects of CO_2 capture technologies with the objective of reducing costs and improving overall system efficiencies;
- Develop national storage capacity estimates; and
- Conduct further work to understand and define the concept of "capture and storage ready" and its value as a viable mitigation strategy.

Recommendations Addressing Institutional Issues

- Establish legal and regulatory frameworks for safe, large-scale geological storage;
- Utilize public-private partnerships and government-government collaboration to accelerate adoption of large-scale CCS projects;
- Raise public education and awareness;
- Address the financing gap facing early projects with higher costs and risks;
- Create a value for CO_2 reductions from CCS projects; and
- Take concerted international action on large-scale integrated CCS demonstration projects and near-term opportunities.

The G8 responded to these proposals at its 2008 meetings in Japan. The G8 Energy Ministers issued a statement at their June meeting stressing the critical role of CCS in tackling the global challenges of climate change and energy security. They also stated collective support for the recommendations developed by the IEA and the CSLF. In particular, they strongly supported the recommendation that 20 large-scale CCS demonstration projects be launched globally by 2010. The G8 Heads of State, meeting in July 2008, also supported actions to advance CCS, again specifically mentioning the 20 demonstration projects.

Implementation of these recommendations has already begun, but much more remains to be done. As discussed earlier, research and development is expanding around the world, particularly to reduce capture costs. Many large-scale demonstration projects have been proposed and legal and regulatory frameworks are being developed. Numerous new projects are now being conducted or planned and these projects build on the results of earlier projects. These projects are also becoming more sophisticated and are moving toward commercial status. They cover most of the varied approaches to both capture and storage.

Conclusion

CCS can be an important, cost-effective and timely part of the solution to climate change. Widespread commercial viability of CSS is feasible by about 2020 with sustained global cooperation by governments and industry. The results so far have been highly positive: a profusion of technologies have emerged; several commercial projects have begun operation, are under construction or are planned; and CCS has become a high priority for many governments and companies.

[2] The full discussions of these recommendations may be found on the websites of the International Energy Agency (www.iea.org) and the Carbon Sequestration Leadership Forum (www.cslforum.org).

Annex: Advancing CCS Technology

CCS has three basic stages: capture, transport and geologic storage. There are multiple options for each stage and all three must be combined into an integrated system. The technologies for all three stages are evolving rapidly.

How CO_2 Capture Works

CO_2 capture involves the separation of CO_2 from other exhaust gases emitted by a power generation or industrial facility and compression of that CO_2 into a supercritical fluid state for transport and storage. In power generation, CO_2 may be separated using one of three methods:

- Post-combustion,
- Pre-combustion, and
- Oxyfiring.

Other methods—membrane separation, chemical looping and cryogenic separation—are at an earlier phase of development. In industrial facilities, CO_2 may be emitted from multiple sources, including chemical reactions. The nature and complexity of industrial facilities varies widely and capture must be integrated into production processes.

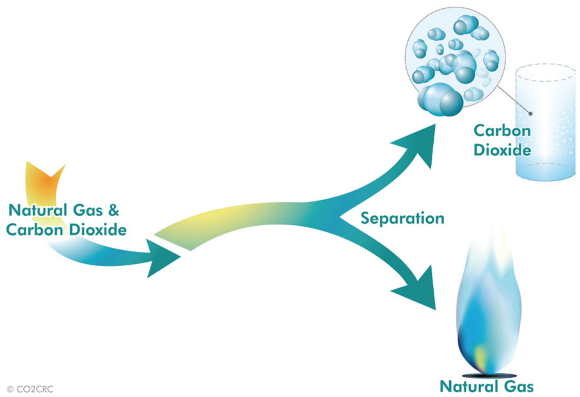
In post-combustion capture, CO_2 is separated from other exhaust gases after combustion of the fossil fuel. Post-combustion capture can be used to remove CO_2 from the exhaust gas streams of facilities such as power plants and industrial facilities. This system is analogous to systems that remove pollutants such as particulates, sulfur oxides and nitrogen oxides from many power plants. Post-combustion capture approaches use chemical or physical solvents to dissolve the CO_2, which is then released for compression at a later stage in the process. The original, and most developed, post-combustion capture concept is amine separation. This concept was derived from the process widely used for separating CO_2 from economically valuable components of natural gas such as methane. That process uses monoethanolamine (MEA) as the solvent. Natural gas from production wells often contains CO_2, and MEA separation is used to remove the CO_2 from those production streams.

Several potential solvents are being considered for post-combustion capture, including various types of amines, amino acid salts, ammonia, sodium carbonate solutions and solvent blends. Amines and ammonia are currently the two leading candidates for post-combustion capture solvents, but what will ultimately prove to be the best solvent has yet to be determined.

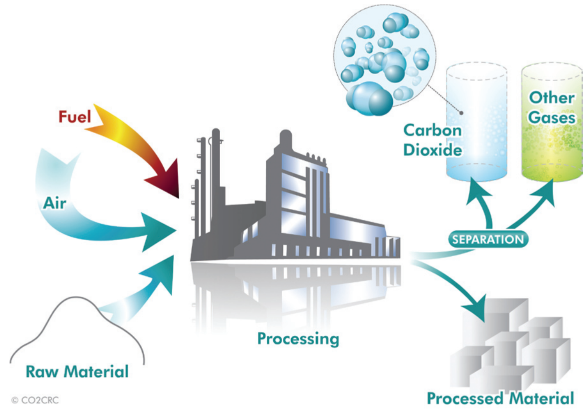
A variant of using solvents is a process called adsorption, in which the CO_2 adheres to the surface of a solid or liquid rather than being dissolved. Solids such as zeolites and activated carbon are being considered for adsorption-based processes.

Post-combustion capture is used today on a small scale in some power plants and industrial facilities. It is employed either to produce CO_2 for industrial uses such as carbonated beverages or in test facilities for CCS. In those power plants and industrial facilities, typically only part of the exhaust stream of the power plant is captured.

Capture from Natural Gas Processing

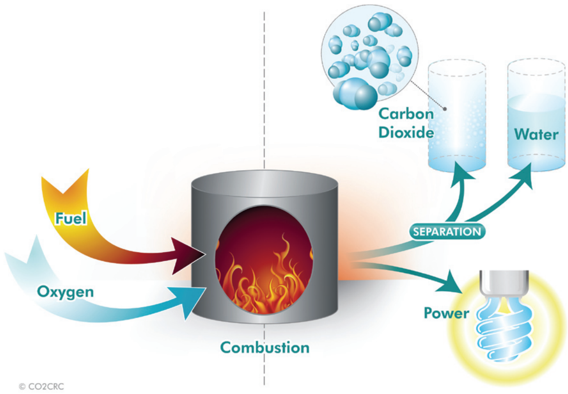


Capture from an Industrial Process

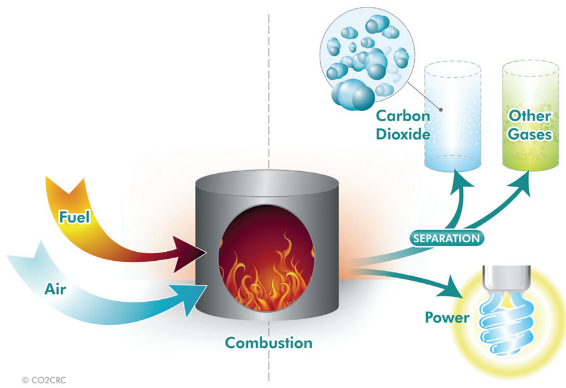


Capture from Power Generation

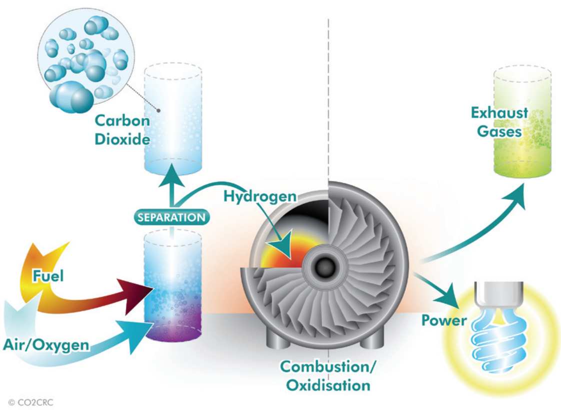
Oxyfiring



Post-combustion



Pre-combustion



A number of options are available for CO_2 capture depending upon the type of source. Capture from natural gas processing and some industrial processes is now fully commercial and widely used. Capture from other industrial processes and power generation is under development.

Image Source: CO2CRC

CO_2 is captured commercially from the flue gas of a natural gas-fired combustion turbine operated by Suez Energy Generation in Bellingham, Massachusetts, U.S.A. The plant uses a proprietary MEA-based solvent.

As part of the Castor project sponsored by the European Commission, 25 tonnes per day of CO_2 were captured from the exhaust stream of the coal-fired Ejsberg Power Station in Denmark operated by Elsam. The project began operation in 2006 and was completed two years later.

Image Source: IEA Greenhouse Gas R&D Programme

The Quest for a Better Solvent

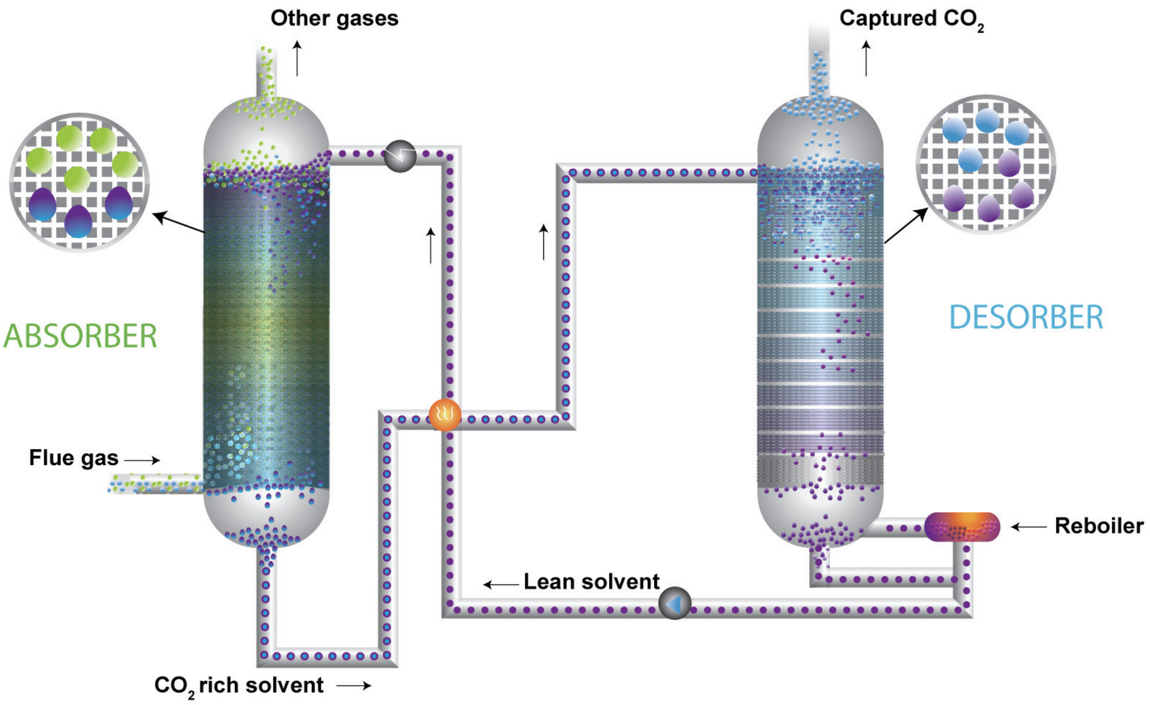
The race is on to find the best solvent for post-combustion CO_2 capture. Many companies believe that whoever finds the best solvent will be rewarded with a huge global market. Academic and government labs are also taking part in the search.

Engineers around the world are working to improve post-combustion capture, especially for coal-fired power plants. New capture systems must work with lower concentrations of CO_2 and the impurities that come with burning coal. No matter what is burned, the most critical component of post-combustion capture is the solvent.

The most common solvent used for CO_2 separation is monoethanolamine (MEA). MEA attaches to CO_2 relatively easily. Breaking apart the mixture and regenerating the pure solvent, however, substantially increases energy use. MEA degrades in the presence of CO_2, and has to be regularly supplemented, yielding a high rate of solvent consumption. MEA is also corrosive and therefore requires materials not prone to corrosion. These properties demand large, specialized equipment and increase capital and operating costs.

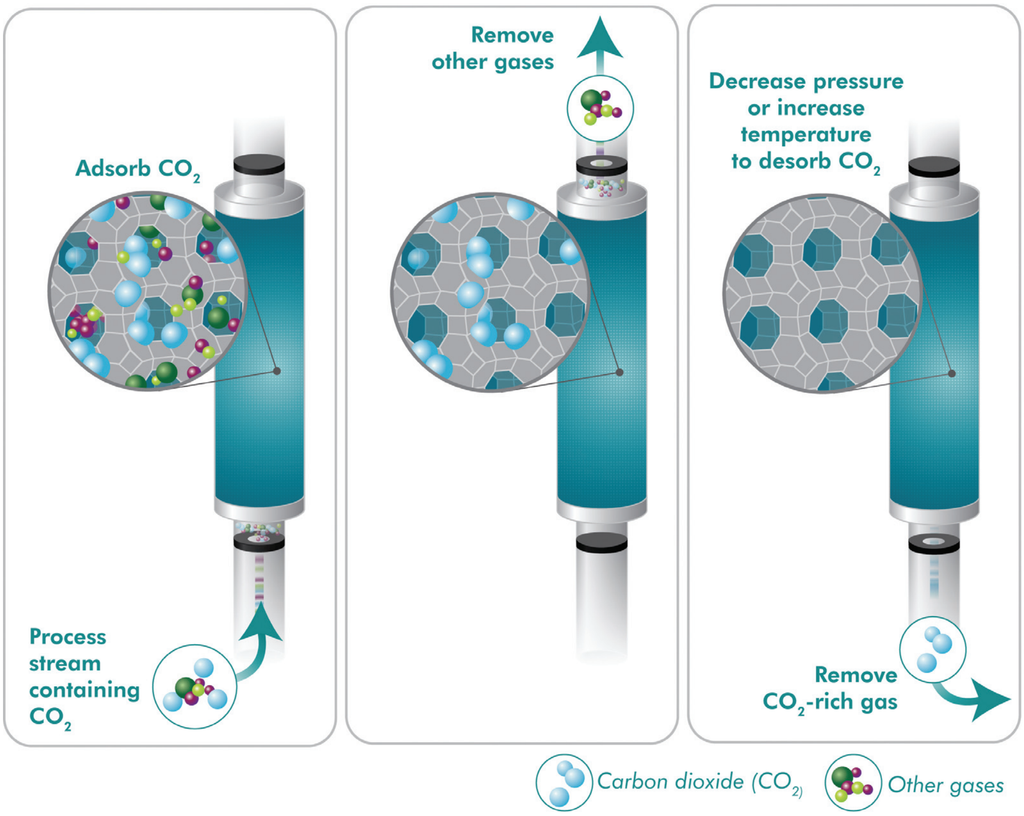
Engineers are looking for ways to improve upon MEA by finding a less degradable and/or corrosive solvent that attaches to and then easily lets go of CO_2. As Stuart Dalton of the U.S.-based Electric Power Research Institute (EPRI) put it, “Anything that likes to catch CO_2 doesn’t like to let it go, and anything that likes to let it go, doesn’t like to catch it. The kinds of compounds that like to bind with CO_2 bind to it pretty well, but to regenerate it typically take a lot of energy.”

Researchers around the world are working hard on developing new and improved solvents. Some are adding or subtracting ingredients from the traditional MEA solvent mix. Others are looking at possible ways to use different amines. Still others have abandoned amines altogether and are working with ammonia, amino acid and/or various different solvents. As of 2008, no improved solvent has been tested on a commercial scale at a coal-fired plant, but many tests, pilot projects and demonstrations are ongoing and planned.



Flue gas containing CO_2 and other gases (mostly nitrogen from the air) enters the chamber containing the solvent. The solvent with the dissolved CO_2 is then removed from the chamber. The other gases are released as they are not absorbed by the solvent. Recovery of CO_2 from the solvent is called desorption. Heat or pressure can be used to trigger the release of CO_2 from the solvent, which may require considerable energy.

Image Source: CO2CRC



Adsorption occurs when a gas accumulates on the surface of a solid or a liquid, known as the adsorbent. Possible adsorbents include metal organic frameworks, zeolites and porous carbons. The gas mixture enters the adsorbent chamber and the CO_2 is trapped in the chamber, while the other gases pass through. The adsorbent with trapped CO_2 is then triggered to release the CO_2 by pressure or temperature, depending on the process.

Image Source: CO2CRC

In <u>pre-combustion capture</u>, CO_2 is separated from a hydrocarbon fuel before the fuel is burned. Solid or liquid fuels such as coal, biomass or petroleum products are first gasified in a chemical reaction at very high temperatures with a controlled amount of oxygen. Gasification produces two gases, hydrogen and carbon monoxide (CO). These same two gases are produced from natural gas through a process called reforming. In reforming, the methane in the natural gas chemically reacts with steam to produce hydrogen and CO. After production by either gasification or reforming, the CO is converted to CO_2 and then removed, leaving pure hydrogen to be burned to produce electricity or used for another purpose. The CO_2 is then compressed into a supercritical fluid for transport and injection.

Gasification has been in use since the 1800s, when it was originally developed to produce town gas for lighting and cooking. Since then, it has been widely used to produce synthetic fuels, chemicals and, recently, electricity. Reforming of natural gas is widely used throughout the world to produce hydrogen and is a well-established commercial practice.

Over 100 gasifiers currently operate worldwide, most of which gasify petroleum products for chemical production. Four coal-fired power plants and about 20 power generation facilities in oil refineries now use a gasification-based system called Integrated Gasification Combined Cycle (IGCC). Considerable experience has already been gained separating CO_2 as a by-product of gasification. This CO_2 is used for various commercial purposes ranging from beverage carbonation to urea production and Enhanced Oil Recovery (EOR). Perhaps the best known gasification plant that captures CO_2 is the Great Plains Synfuels Plant in North Dakota. Other gasification plants have captured CO_2 for industrial purposes. These include:

- Tennessee Eastman, Kingsport, Tennessee, U.S.A.—for the food and beverage industry;
- Texaco Refinery, Los Angeles, California, U.S.A.—for enhanced oil recovery (EOR);
- Eight gasification plants in China—for urea production; and
- Coffeyville, Kansas, U.S.A.—for urea production.

<u>Oxyfiring</u> (sometimes called oxy-combustion, oxyfuel or oxy-coal) is the combustion of fuel in an oxygen-rich environment. Oxyfiring has been used on a small scale for high-temperature industrial processes since the 1940s. Large-scale oxyfiring of coal to increase CO_2 concentrations for CCS has been studied since the late 1980s. When fuel is burned in air, CO_2 concentrations are relatively low since most of the air consists of nitrogen. Higher CO_2 concentrations are expected to make separation less expensive. Burning fuel in pure oxygen creates temperatures well beyond what the steel used in a boiler could tolerate. To avoid that, flue gas containing CO_2 is recycled into the boiler (in place of the nitrogen

The Great Plains Synfuels Plant gasifies coal to produce synthetic natural gas and various chemicals. The plant captures 2.8 million tonnes of CO_2 per year, which is transported by pipeline to Saskatchewan, Canada for use in Enhanced Oil Recovery (EOR). This facility has been capturing CO_2 since 2000.

Image Source: Dakota Gasification Company present during combustion in air). Pollutants are removed, the flue gas is cooled and then CO_2 is extracted and compressed. Oxyfiring has been proposed for both new and retrofit applications.

Oxyfiring has been tested in a number of small experimental facilities for many years. For example, the CANMET Energy Technology Center, a division of Natural Resources Canada, has operated a pilot scale oxyfiring facility in Ottawa, Ontario, Canada since 1994. That and other facilities have provided much of the data required to ready oxyfiring for use on a somewhat larger scale in actual power plants. The first coal-fired power plant with oxyfiring went on line in Germany in 2008.

Oxygen production: a key enabling technology. Both gasification (used in pre-combustion capture) and oxyfiring require large amounts of oxygen. Currently this oxygen is produced by cryogenic air separation. Cryogenic air separation adds to capital costs. It typically constitutes about 10 percent of the capital cost of a coal gasification plant and adds to its complexity. Cryogenic oxygen production also consumes considerable energy—about 15 percent of fuel consumption for oxyfiring. Reducing oxygen production costs and energy use would benefit both oxyfiring and pre-combustion capture.

Emerging capture processes. Several other capture methods are in early development:

- Membrane separation is a post-combustion method which uses a semi-permeable barrier (the membrane) through which one or more of the gases in a mixture of gases moves faster than the others, thus separating the components. Membrane separation methods for oxygen production are also being developed that would enhance both oxyfiring and pre-combustion capture. They have the potential to be more efficient and less capital intensive than solvent-based systems.
- Chemical looping combustion uses metal oxide particles to react with a solid, liquid or gaseous fuel, producing solid metal particles and a mixture of carbon dioxide and water vapor. The water vapor is condensed, leaving pure carbon dioxide.
- Cryogenic separation and distillation takes advantage of different temperatures at which CO_2 and other components of an exhaust stream change from a gas to a liquid or vice versa.
- Advanced compression processes utilize new principles such as ramjet compression, which have the potential to be more efficient and less costly than turbine-driven compressors currently in use.

Capture from industry. Several types of industrial manufacturing facilities could potentially capture CO_2. CO_2 is now commercially separated from natural gas production streams and in plants that produce ammonia or hydrogen. CO_2 could also be captured from other industries including integrated steel mills, cement plants, oil refining, petrochemicals, cement plants, pulp and paper production, processing of heavy oils such as tar sands, and synthetic fuels production. Methods to capture CO_2 at each of these types of facilities depend on their specific production processes, which can be quite complex. Some facilities such as oil refineries and petrochemical plants may emit large amounts of CO_2 in total, but the CO_2 may actually be emitted from many different individual sources within the facility. Each source may emit a different quantity of CO_2 at a different pressure and purity. The CO_2 emitted from some types of operations—cement kilns and iron reduction, for example—may come from chemical reactions involving the raw materials. In each case, the capture methods must be tailored to the specifics of the production process. Adaptations of post-combustion, pre-combustion and oxyfiring approaches have been proposed for various types of industrial facilities.

Improving Capture Technologies

The major challenge associated with capture is to reduce costs for low-concentration, low-pressure, high-volume sources such as power plants. For power generation, several alternative technology approaches potentially offer substantial cost reductions. Each approach has strong advocates in the scientific and engineering community. It is not clear which approach will ultimately prove most cost-effective. It is still early in the development of CCS and new and innovative ideas continue to emerge. It is possible that different approaches may prove most attractive under different circumstances.

Post-combustion capture faces three challenges in power generation facilities compared to its use in currently-commercial industrial processes. In power generation:

- The CO_2 concentration is lower (typically 10-20 percent versus 27-33 percent);
- CO_2 is emitted at atmospheric pressure, requiring considerable compression;
- The scale is larger—up to several million tonnes (metric tons) per year.

Larger and more-expensive equipment and more energy are required to separate and compress the CO_2 in power generation. Currently-commercial capture facilities also produce CO_2 for an end-use (such as EOR or food production) where the CO_2 has a higher financial value than simply avoiding CO_2 emissions.

Considerable work is taking place to develop improved post-combustion systems for CCS in power generation applications. This work has several basic improvements as goals:

- Improving capture using MEA,
- Finding solvents that require less energy to release the CO_2,
- Extending the life of expensive solvents,
- Advancing designs and materials for greater

Large-Scale Post-Combustion Projects

Pilot projects that capture CO_2 from a portion of power plant exhaust gases provided the information necessary for some post-combustion approaches to removing CO_2 from power plants on a larger, commercial scale.

- **Mountaineer and Oolagah.** The U.S. power company American Electric Power (AEP) plans to install a chilled ammonia post-combustion capture system developed by Alstom at its Mountaineer power plant in West Virginia in 2009. The unit will capture 200,000 tonnes of CO_2 per year from a 30 Megawatt installation and inject it into saline formations under the site. AEP will use the information gathered at Mountaineer to design and install the same technology on a 450 Megawatt coal-fired generation unit at Oolagah, Oklahoma in 2012. It will capture about 1.5 million tonnes of CO_2 per year for use in EOR.

- **U.K. Competition.** The United Kingdom government has solicited bids for a commercial-scale post-combustion power demonstration project at a coal-fired power station, with CO_2 stored offshore. The U.K. government will pay for the full cost of capture and storage. CCS is to be demonstrated by 2014 in a project of at least 300 Megawatts.

- **Norwegian natural gas power plants.** Two Natural Gas Combined Cycle (NGCC) power plants in Norway are planned with post-combustion capture. An NGCC plant at the Mongstad Refinery will capture 100,000 tonnes of CO_2 in 2010 and 1.1 to 2.1 million tonnes by 2014. This plant will become the European Test Centre Mongstad. Capture will also be implemented at the existing Kårstø NGCC plant.

Several other large-scale post-combustion projects are also planned.

removal efficiencies and larger scale, and
- Improving compression technologies.

Pre-combustion capture may be used for IGCC power plants, gasification plants that produce synthetic fuels or chemicals (like the Great Plains Synfuels Plant), or for power generation using natural gas. Gasification coupled with pre-combustion capture is a well-established technology. IGCC technology has been widely used in oil refineries to produce electricity using low value byproducts for many years. The IGCC used at refineries, however, is somewhat simpler than the power industry needs and uses less-expensive refinery byproducts as fuel.

IGCC has the potential to generate power and capture CO_2 with relatively high efficiency at a competitive cost. Capturing CO_2 from IGCC is not a major challenge—several commercial processes are available. Moreover, IGCC produces CO_2 at a higher pressure, so compression costs are reduced compared to other capture methods. The challenge is to reduce the cost of building and operating the entire IGCC plant to make it commercially feasible for the power industry. The best ways to do so are being worked out now.

Even without CO_2 capture, IGCC is a highly complex system with several major components. Those components must be integrated to be efficient, reliable and cost-effective. Those components are the gasifier; combined cycle power generation equipment; oxygen plant (in most designs); and, if incorporated, CO_2 capture equipment. Several different gasifiers and types of capture equipment can be used, each of which performs differently. Alternative gasifiers have varying abilities to gasify different fuels and the components can be tied together in many different ways. A critical piece of equipment for an IGCC or natural gas plant with capture is a combustion turbine that runs on hydrogen. That type of turbine is still under development.

Large-Scale Pre-Combustion CCS Projects

IGCC with CCS under construction. The Dutch utility Nuon is retrofitting its Buggenum IGCC plant to capture 30,000 tonnes per year of CO_2 starting in December 2008. That plant gasifies both coal and biomass. The first 250 Megawatt phase of the GreenGen IGCC project in Tainjin, China is planned to capture CO_2 at pilot scale in 2009. Later phases will expand the plant to 650 Megawatts and capture CO_2 at commercial scale. China Huaneng, China's largest power generator, is building GreenGen with the support of the Chinese government and several partners.

Planned IGCC with CCS. In the U.S., the Department of Energy's FutureGen project was restructured in 2008 from one advanced research facility to multiple commercial projects. A solicitation with multiple awards is underway. BP and Rio Tinto are planning an IGCC project that will use refinery byproducts as fuel and capture CO_2 for enhanced oil recovery in Kern County, California. The European Commission is planning to build CCS into an advanced IGCC unit known as Hypogen starting around 2012. Meanwhile, European utility RWE also plans a 450 Megawatt lignite IGCC with CCS for 2014 in Germany. Additionally, U.K. power producer Powerfuel Power Ltd expects the 900 Megawatt IGCC plant it plans to build in Hatfield will start capturing CO_2 in 2013. ZeroGen is a planned IGCC plant with CCS in Australia. ZeroGen is to be built in two stages. An 80 Megawatt demonstration plant will capture 75 percent of the CO_2 emissions by 2012. Next, a 300 Megawatt full-scale commercial plant will capture 90 percent of the CO_2 emissions by 2017.

Several other IGCC plants with CCS have been announced, but are not as far along in planning or have not definitively committed to incorporating CCS.

Several major equipment manufacturers and engineering companies have formed teams to commercialize IGCC. They have invested heavily in developing the technology. IGCC without capture is now offered commercially to power generators and the first orders for these plants have been placed. Even without capture, IGCC is unfamiliar to the power industry and costlier than conventional steam boiler coal plants. Integrating capture will take further time and investment. When the challenge of integration is overcome, IGCC with capture has the potential to perform with higher efficiency and lower cost than the alternatives.

Oxyfiring is the least advanced of the three major capture options for power generation. It faces three technical challenges:

- The high cost of oxygen production (a challenge shared with pre-combustion capture),
- Overall design of the boiler and burners, and
- Removal of impurities from the CO_2 stream.

Several small facilities are exploring methods to overcome these challenges. Several oxyfiring pilot projects are planned and one is now in operation.

Capture from most large industrial facilities and other sources of CO_2 faces greater challenges. Capture technologies for industrial processes such as steel- and cement-making must be specifically designed for those types of facilities. Industrial facilities can be very complex and have many individual sources of CO_2 embedded within them, sometimes with large individual emissions. In addition, much

Power Plants with Oxyfiring

The first coal-fired power plant with oxyfiring went on line at the Schwarze Pumpe power station owned by Vattenfall in eastern Germany in September 2008. This 30 Megawatt pilot plant burns both brown (lignite) and hard (bituminous) coal and captures CO_2. The CO_2 is carried by truck 320 km (200 miles) for injection into an onshore depleted gas field. According to Vattenfall, the plant is to validate engineering work, learn and better understand the dynamics of oxyfiring and demonstrate capture technology. Learning from Schwarze Pumpe, Vattenfall plans to demonstrate oxyfiring at a 250 Megawatt boiler at its Janschwalde plant in 2013. Another boiler of the same size at Janschwalde will also demonstrate post-combustion capture.

Australian power generator CS Energy and several partners are planning to retrofit the Callide A power station in Queensland with oxyfiring technology in a project partly funded by the Australian and Japanese governments. The project will demonstrate a completely integrated oxyfiring process at a coal-fired power plant. It will obtain design and operational experience with oxyfiring for future oxyfiring plants. Retrofitting involves refurbishment of a 30 Megawatt coal-fired boiler for oxyfiring operation and the addition of both a cryogenic air separation unit to produce oxygen and a CO_2 capture and purification unit. The plant will capture about 75 tonnes of CO_2 per day. The project is in the pre-construction phase with funding and final agreements approved. The storage site will be selected in 2009. Capture and storage will begin in 2011.

The French oil company Total is planning to begin operation in late 2008 of a pilot oxyfiring plant at the Lacq gas processing plant in southern France. A boiler at that plant is being converted into an oxyfiring combustion unit. Captured CO_2 will be transported through a 27-kilometer pipeline for injection into the nearly-depleted Rousse natural gas reservoir at a depth of 4,500 meters. The pilot plant will emit up to 150,000 tonnes of CO_2 over a two-year period. The pilot will also contribute to the goal of CO_2 emissions-free power generation defined by the European Technology Platform, in which Total is a partner.

of the CO_2 in many industrial processes—steel production, chemicals, cement—comes from chemical reactions inherent in their operation, not from the burning of fuel. Capturing CO_2 from these processes will require modifications to long-established production methods and integration with those processes. Much of the growth in these industries will be in developing countries such as China. Compared to power generation, relatively little effort so far has gone into capture from these processes.

One industrial process for which capture is now being extensively worked on is the production of synthetic crude oil from oil sands in western Canada. CO_2 is produced in this process in two ways. Boilers produce steam for injection underground and emit CO_2 and hydrogen is produced by reforming natural gas for upgrading heavy oil, which also emits CO_2.

The extreme edge of difficulty would be to capture CO_2 from the atmosphere itself. CO_2 is only about 0.04 percent of the atmosphere and it is obviously at atmospheric pressure, requiring extensive compression. Even so, a number of research teams are working on air capture. Success and cost-effectiveness are not guaranteed, but Sir Richard Branson has offered the $25 million Virgin Earth Challenge prize for a commercially viable air capture design.

Reducing Energy Use of Capture

All three capture options for power generation have higher capital and operating costs as well as lower efficiencies than conventional power plants without capture. Costs are higher than for plants without CCS because more equipment must be built and operated. Ten to 40 percent more energy is required with CCS than without. Energy is required mostly to separate the CO_2 from other gases and to compress it, but some is also used to transport the CO_2 to the injection site and inject it underground.

As CCS and power generation technology become more efficient and better integrated, the increased energy use is likely to fall well below early levels. Much of the work on capture is focused on lowering costs and improving efficiency as well as improving the integration of the capture and power generation components. These improvements will reduce energy requirements. At the same time, work is underway to increase the overall efficiency of power generation. More efficient combustion turbines, ultrasupercritical steam power plants and IGCC plants are being developed. Advanced power plants with CCS may eventually be as efficient as today's power plants without CCS.

CO_2 Transport

The best way to have CO_2 in supercritical fluid form reach the injection site is to build the capture facility directly over the site, eliminating the need for transport. Otherwise, CO_2 transport is needed. Small amounts of CO_2 are now transported by truck for use in the beverage, dry cleaning and dry ice industries. In contrast, the large quantities of CO_2 to be transported from power plants or industrial facilities would generally necessitate pipeline transport. Ocean-going ships have also been suggested for very long-distance transport, but none has yet been built.

CO_2 pipelines have operated for many years and are well established. The United States has an extensive pipeline network that has been in operation for many years that carries CO_2 from naturally-occurring fields and capture plants to depleting oil and gas fields. There it is used to increase production in Enhanced Oil Recovery (EOR). CO_2 is also transported 320 km (200 miles) from a gasification plant in North Dakota to two mature oil fields in Saskatchewan, Canada for EOR. Another pipeline network carries CO_2 between capture facilities and large greenhouses in the Netherlands where it is used to stimulate plant growth. In the Snøhvit CCS project, CO_2

A network of commercial pipelines safely brings CO_2 from natural sources and capture facilities to EOR operations in the United States and Canada.

Source: United States Department of Transportation

is transported in an undersea pipeline from a capture facility on the Norwegian coast to an offshore storage reservoir.

How Geologic Storage Works

In CCS, CO_2 is injected into deep geologic formations that can securely contain it. Potential sites for geologic storage include depleted oil and gas fields, deep saline formations and deep unmineable coal beds. Each of these types of geologic formations holds or has held large quantities of fluids for long periods—often millions of years—using various natural trapping mechanisms. Geologic storage uses the same trapping mechanisms. (See box.) The security of geologic storage is covered in detail in a companion booklet published by the IEA Greenhouse Gas R&D Programme, "Geologic Storage of Carbon Dioxide: Staying Safely Underground." In addition, basalt and shale formations have also been suggested for geologic storage, but much more research must be done before they can be used as CO_2 storage reservoirs.

For more than 30 years, oil and natural gas producers have injected CO_2 to force out stubborn pockets of oil from maturing fields, a process known as Enhanced Oil Recovery (EOR). Once underground injection of CO_2 is finished, the injection well can be capped and the CO_2 stored underground. Increased oil production can help offset the costs of CCS, but EOR opportunities are limited compared to the vast amounts of CO_2 that must be disposed of. Similar processes are being developed for Enhanced Gas Recovery (EGR) and Enhanced Coal Bed Methane (ECBM).

Geologic storage activities are conducted in three phases: planning and construction, injection, and post-injection. In the planning and construction phase, sites are first identified and characterized and then wells for injection and monitoring are drilled based on the geologic data. During the injection phase, which may last 20-40 years, CO_2 from the source is injected into the selected reservoir formation and is monitored to ensure that the CO_2 stays safely in place. Monitoring may continue for some time in the post-injection phase.

Geologic storage of CO_2 has already been conducted on a commercial or test basis at several sites throughout the world. These sites include depleted oil and gas fields, saline formations and coal beds. Many further projects are planned over the next several years. Four integrated CCS projects involving geologic storage are now commercial: Sleipner and Snøhvit offshore from Norway, In Salah in Algeria and Weyburn-Midale in Canada. Weyburn-Midale also hosts a major research project conducted by the IEA Greenhouse Gas R&D Programme. Much useful information has been produced by these projects.

CCS has already been used in several commercial projects and experimentally in a number of others. Several technical challenges must be overcome, however, for widespread use of CCS in large-scale integrated projects. Extensive work is being conducted throughout the world to meet these challenges.

Improving Geologic Storage

Widespread implementation of geologic storage requires a more complete understanding of what happens when large volumes of CO_2 are injected under diverse geologic conditions. This will facilitate the developing storage practices that can be tailored to the wide variety of geological conditions likely to be encountered. Experience so far has been in a limited number of

What Keeps the CO_2 Underground?

CO_2 is injected under extremely high pressure as a supercritical fluid into tiny pores within deep rock formations which have already trapped liquids such as oil, natural gas or highly salty and unusable water for millions of years. Supercritical CO_2 takes up as little as 0.27 percent of the space of gaseous CO_2 and diffuses readily through the pore spaces of solids. Supercritical CO_2 compresses more the deeper it is injected, increasing the amount that can be stored in the same volume of rock. High pressure and sufficient depth (2,600 feet or 800 meters) maintains the supercritical fluid state. Once in an appropriate geologic storage space, CO_2 is held in place by one or more of five trapping mechanisms, depending upon geology:

- Stratigraphic trapping uses cap rock, a dense layer of impermeable rock that overlies the CO_2 deposit forming a closed container.
- Structural trapping occurs when impermeable rocks overlie a fault or fold in the geologic strata, holding the CO_2 in place. The CO_2 is also generally separated from the surface by other thick layers of impermeable rock called seals.
- Residual trapping takes place when the CO_2 is trapped in the tiny pores between rocks by the capillary pressure of water.
- Solubility trapping occurs when CO_2 dissolves in the saline water in the rock formation, forming a denser fluid which may then sink to the bottom of the storage reservoir.
- Mineral trapping occurs when CO_2 chemically combines with the surrounding rocks to form minerals.

The security of geologic storage is discussed in more detail in a companion booklet from the IEA Greenhouse R&D Gas Programme—"Geologic Storage: Staying Safely Underground."

geologic settings. The behavior of trapping mechanisms, the migration of displaced fluids (such as saline water), potential leakage mechanisms, and the mechanical impacts on geologic structures all need to be better understood for different types of reservoirs. To a large extent, geologic storage builds on decades of experience in oil and gas production and the underground injection of other fluids. Yet, there are differences due to the large volumes of CO_2 that will be injected and CO_2's physical and chemical properties. Site characterization and selection, storage planning and operational practices must be further developed so that they can be widely and safely conducted for different geological conditions in each type of reservoir. Methods for monitoring CO_2 storage and, if necessary, remediation, must be tested and validated. Much of this work is already underway.

Geologic storage challenges can be overcome by gaining experience injecting CO_2 in a diverse set of storage reservoirs and sharing the information. So far, however, CO_2 has been injected at a small number of sites, mostly in relatively small amounts. Much of this work has been done by leading experts and the results so far are encouraging, but geological conditions are extremely diverse. Many future projects will be undertaken by commercial organizations in geologies different from those where experience has been gained so far. Large quantities, on the order of several million tonnes of CO_2, must be

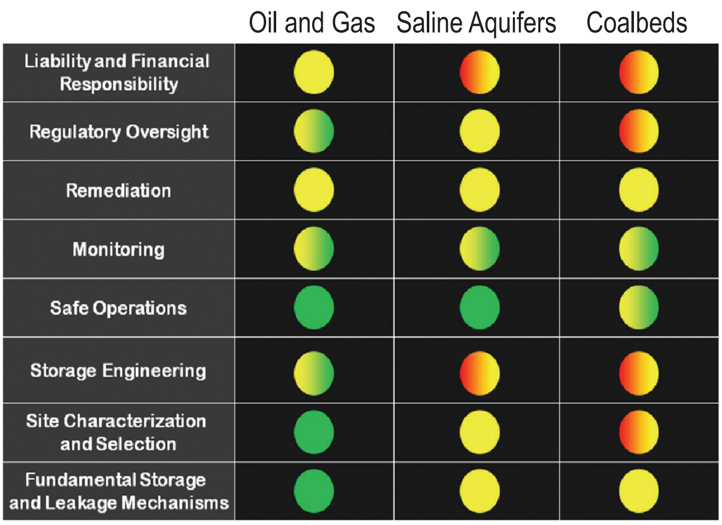
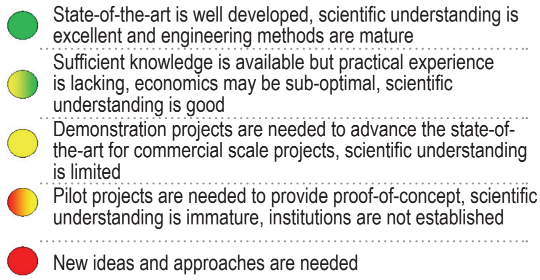


Image Source: Sally Benson, Stanford University



The current state-of-the-art of geologic storage knowledge and practice varies depending upon the type of storage reservoir and the specific aspect or function. The most experience is in oil and gas reservoirs, where CO_2 injection has been used for decades for EOR.

The Otway Project

In April 2008, Australia's Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) started injecting CO_2 into a depleted natural gas field as part of the first underground carbon storage project in the southern hemisphere—the Otway Basin Pilot Project. The injection site in southwestern Victoria is expected to eventually hold 100,000 tonnes of CO_2. Most importantly, it will yield detailed technical information on storage processes, injection technologies and comprehensive monitoring techniques as well as verification procedures. As of September 2008, more than 21,000 tonnes of compressed, naturally occurring CO_2 had been safely injected. The injection process will last two years, but monitoring and modeling activities will go on for several years after injection ceases.

Otway and similar projects around the world are developing the broad base of information that will enable geologic storage in diverse geologic settings.

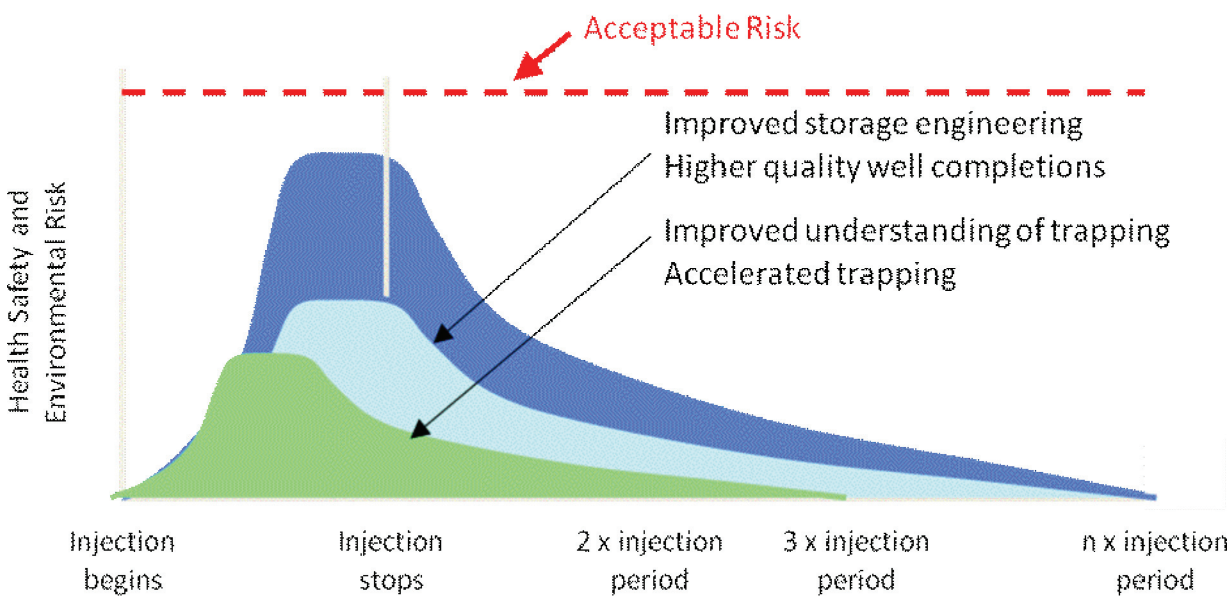
injected into a greater number of sites. This will enable geologists and engineers to more fully understand what happens underground and to develop commercial practices for all aspects of geologic storage. Based on the information gained from this further work, effective practices must be developed for commercial operations in a wide range of geological settings.

Research so far indicates that risks such as movement of CO_2 out of the storage formation are extremely unlikely if the storage is conducted properly. Further research is necessary to fully quantify risks in different geological circumstances and to develop methods for avoiding them. Researchers are conducting experiments and analyses to better understand potential risks. This work involves studying how CO_2 behaves in underground geologic formations and how it is affected by each of the trapping mechanisms. Such an understanding must be gained for the wide range of geological conditions under which storage may eventually take place. The goal is to ensure that planning can be conducted with confidence and that operations and closure are safe and secure. Criteria are being developed, for example, to ensure that commercial projects are below an acceptable level of risk. In addition, work is being conducted to enhance and further develop equipment and protocols for measurement, monitoring and verification and for practices to remediate any leaks that might occur. Experimental work currently being conducted and planned over the next few years is likely to generate much of the needed information.

Analyses indicate that the overall risk is highest toward the end of the injection period and then decreases to become virtually nonexistent over time. Improved storage engineering and greater understanding of trapping mechanisms will lower the risks. The pattern of risks over time also has significant implications to the financing and regulation of geologic storage.

Integration and Scale Challenges

Integration of capture equipment with the CO_2 source facility is a significant challenge. Source facilities exist to produce a useful output, whether electricity, natural gas, steel, cement, chemicals or other products. They burn fuel, generate steam and may operate various other chemical process-



Methods are being developed to estimate potential risks and how they change over time. Only projects for which the risks are sufficiently low will be undertaken. Improved geologic knowledge and storage engineering practices would reduce risks of geologic projects.

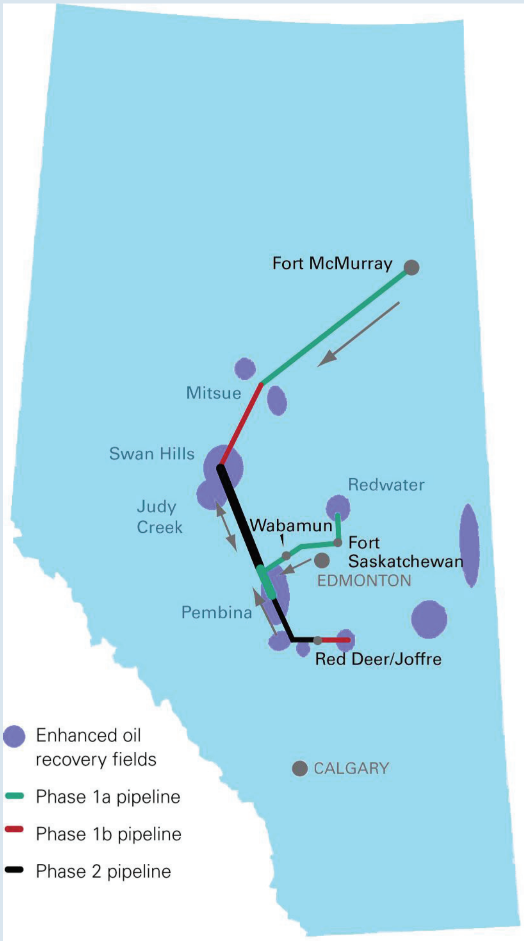
Image Source: Sally Benson, Stanford University es. All facilities must be carefully integrated in terms of process flows, pressures, volumes and heat transfers to be efficient and cost effective. Integration is both a design and an operational issue. CO_2 capture adds a new and potentially significant process that could change how the entire plant is integrated. On the other hand, integrating the capture, transport and storage stages with one another mostly just involves matching the capacities of each stage and coordinating operations.

Integration is particularly a challenge for pre-combustion capture in IGCC power plants. IGCC plants are very complex chemical process facilities that are only now reaching technical maturity. One additional challenge for pre-com-

An Integrated CCS Network in Canada

A group of Canada's largest industrial companies is working out a way to capture CO_2 from a number of different sources and transport it via pipeline to a common storage area. The Integrated CO_2 Network (ICO2N) initiative is focused on developing an integrated infrastructure to reduce the costs and risks of CCS and to accelerate its deployment.

ICO2N is planning an integrated CO_2 transport, EOR and direct storage infrastructure. This infrastructure will move CO_2 produced in Alberta's industrial areas to the Western Canada Sedimentary Basin (WCSB) for EOR and direct storage. The WCSB is a vast sedimentary basin underlying 1.4 million square kilometres (540,000 square miles) of western Canada including southwestern Manitoba, southern Saskatchewan, Alberta, northeastern British Columbia and the southwest corner of the Northwest Territories. Not only is the CO_2 storage potential huge, the WCSB also offers the prospect of reducing the overall cost of the project by using the CO_2 for Enhanced Oil Recovery (EOR).



ICO2N's CO_2 sources in Alberta will be coal-fired power plants near Edmonton, oil sands facilities near Fort McMurray, oil upgrading and refining facilities in and around Fort Saskatchewan and a number of chemical and agricultural industrial facilities near Red Deer.

Linking the CO_2 sources with the injection and/or EOR sites requires building a high-pressure CO_2 pipeline network. That pipeline would consist of a large main line connecting CO_2 capture facilities with the main EOR market and storage locations across the WCSB. ICO2N says the pipeline would likely be built to accommodate the needs of early adopters of carbon capture and then could be expanded in phases. According to ICO2N, its studies indicate that the project has the potential to reduce CO_2 emissions by more than 20 million tonnes per year over the next decade, the equivalent of taking four million cars off the road.

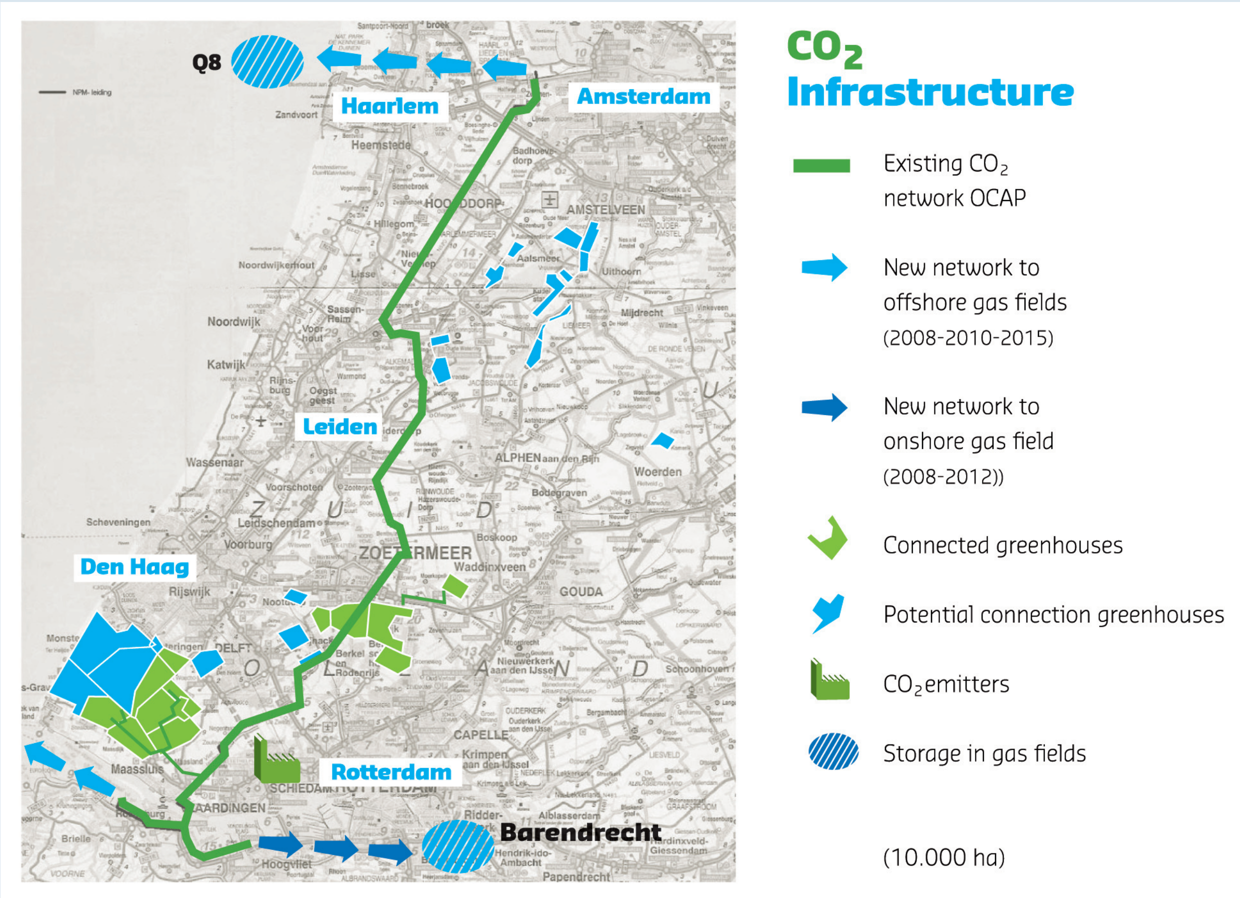
The proposed Canadian network, ICO2N, would connect multiple energy facilities in northern Alberta with a variety of CO_2 reservoirs further south. This map represents one of several possible routings.

Image Source: ICO2N

Rotterdam Climate Initiative

Rotterdam in the Netherlands set out to cut greenhouse gas emissions 50 percent from 1990 levels by 2025, while promoting the economy of the entire Rotterdam region. The Rotterdam Climate Initiative (RCI) is a program that involves government, environmentalists and industry as well as the Port of Rotterdam Authority. Since Rotterdam is the largest port in Europe, the city of Rotterdam and the surrounding area grew to be an industrial powerhouse that now emits enormous amounts of CO_2.

The RCI is a comprehensive plan to reduce CO_2 emissions by combining increased energy efficiency, reuse of waste heat, large scale use of biomass and CCS. One of the main ways RCI plans to cut CO_2 emissions is through the use of a CCS network. The Port of Rotterdam has a concentration of large, energy-intensive industrial facilities. Several oil refineries already capture CO_2, which is piped through an already-existing pipeline network to large industrial greenhouses. Plans are for more of Rotterdam's industries—including several new power plants—to add carbon capture capability. More CO_2 will be captured than the greenhouses will use and this CO_2 will be stored underground. The existing pipeline network will be expanded short distances to deep saline formations for CO_2 storage both onshore and offshore under the North Sea.



The Rotterdam Climate Initiative is developing a CCS network that will capture CO_2 from several industries, expand an existing CO_2 pipeline network, and inject CO_2 into both onshore and offshore storage. Combined with other measures, this Initiative is projected to cut the region's industrial CO_2 emissions in half by 2025.

Image Source: Rotterdam Climate Initiative bustion capture is the development and testing of combustion turbines that operate on pure hydrogen. As with pre-combustion, capture is inherently a part of the oxyfiring production process. Post-combustion capture probably requires less integration, but still affects the flow and constituents of exhaust gases and this impacts the overall balance of pressures in a power plant and the treatment of exhaust gases.

Integration challenges are all solvable. Process engineers have been solving such problems for decades. Typically, many alternative solutions are possible early on. Finding the most cost-effective solutions requires experience and usually some trial and error. Individual components may already be mature in some applications, but experience with integration is needed, especially at large scale.

Scale presents several challenges. The size of many future commercial CCS projects will be larger than previous projects. Many hundreds of CCS projects will eventually be built. Equipment originally designed for smaller projects will need to be scaled up to commercial sizes. This type of challenge is frequently addressed by engineers, but it requires time, effort and learning. Many other greenhouse gas abatement options also face the same challenge of scale.

As CCS becomes more widespread, multiple CO_2 sources and reservoirs will be joined into networks tied together by a web of pipelines. Building common facilities and using them as a system could potentially bring substantial savings. Several such networks are under consideration. One such regional network is currently being planned for western Canada by the ICO2N project. Others have been proposed, notably in Europe. Networks could also tie together industrial facilities that would otherwise be too small for CCS individually into a network that would be economically viable as a group. The Rotterdam Climate Initiative in the Netherlands is planning such a grouping.

Notes

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