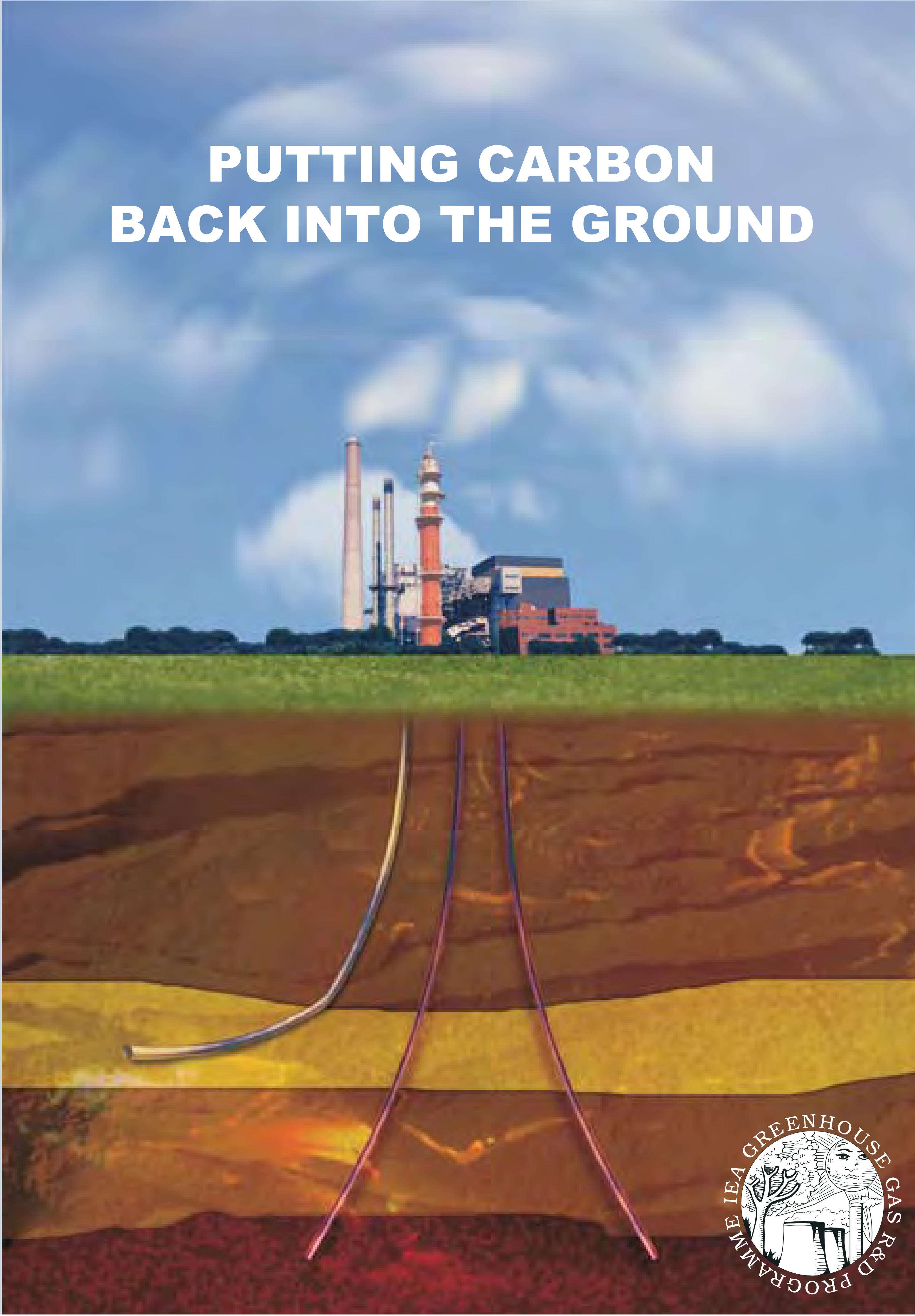
PUTTING CARBON BACK INTO THE GROUND



IEA GREENHOUSE GAS R&D PROGRAMME

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This report has been compiled by J. Davison, P. Freund, and A. Smith.

Cover image by Cotswold Design Studio (Cheltenham, UK).

ISBN 1 898373 28 0

Cover printed on 350g Nimrod

Text printed on 170g Celestial Gloss

CONTENTS

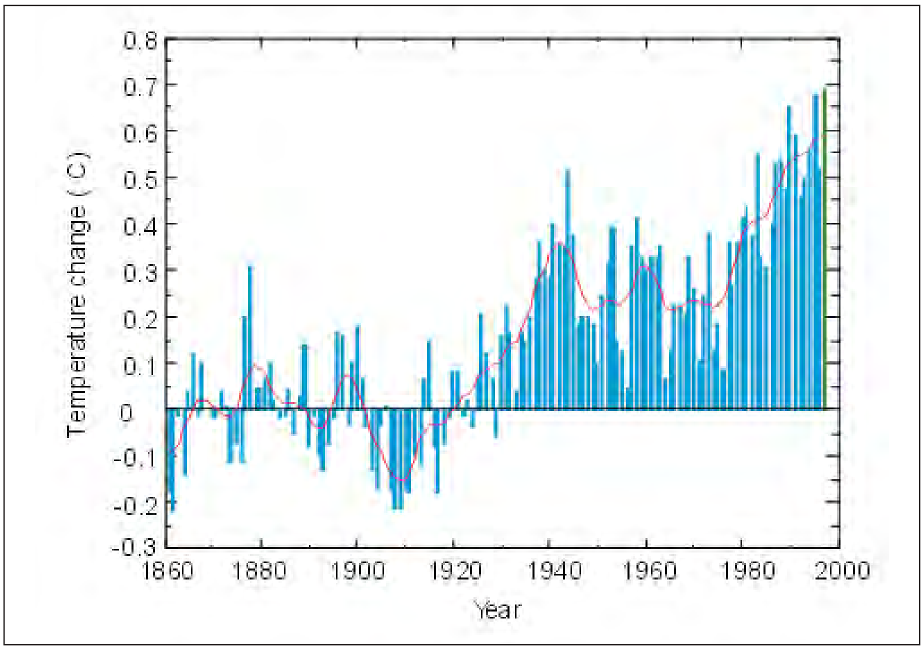
INTRODUCTION

The need to reduce greenhouse gas emissions

Increasing concentrations of CO_2 and other greenhouse gases in the Earth's atmosphere are enhancing the natural greenhouse effect, leading to changes in the climate. The nature, extent and timing of these changes are uncertain but one of the main changes is expected to be a rise in the global average temperature. Figure 1 shows how the observed average temperature has already increased beyond the likely range of natural variability due to external influences such as volcanic dust and the sun's output.

Figure 1
The observed change in global mean temperature at ground level

(Courtesy of the UK Met. Office)



It is now generally accepted that limits will have to be placed on the atmospheric concentration of CO_2 and other greenhouse gases in the atmosphere. The UN Framework Convention on Climate Change (UNFCCC) is intended to address this issue. Through the Kyoto Protocol, developed countries agreed to reduce their emissions by 5.2% below 1990 levels, although this protocol has not yet been ratified. However, CO_2 levels are likely to continue increasing, so greater reductions in emissions will be needed in future – for example, emissions of CO_2 may need to be reduced by more than 60% by 2100, in order to stabilise the atmospheric concentration of CO_2 at no more than 50% above its current level.

Techniques for reducing atmospheric CO_2 levels

The main anthropogenic greenhouse gas is CO_2 - this is the subject of this report. Other greenhouse gases, such as methane and nitrous oxide, are not discussed here but opportunities for abatement of methane emissions are summarised in another report by the IEA Greenhouse Gas R&D Programme (see bibliography).

The main techniques which could be used to reduce CO_2 levels in the atmosphere are:

- Reduce the consumption of energy services
- Increase the efficiency of energy conversion or utilisation
- Switch to lower carbon content fuels, e.g. natural gas instead of coal
- Enhance the sinks for CO_2, e.g. forests, soils and the ocean, which draw-down CO_2 from the atmosphere
- Use energy sources with very low CO_2 emissions, such as renewable energy or nuclear energy
- Capture and store CO_2 from fossil fuel combustion.

The extent to which each of these techniques is used will depend on many factors, including the emission-reduction targets, costs, available energy resources, environmental impact and social factors.

Measures for reducing energy consumption and switching to low carbon fuels are cost-effective in many places today and will deliver useful reductions in emissions. Enhancing natural sinks could make a significant contribution in the short term but the capacity of the sinks is limited and carbon stored in, for example forests, is not always secure. Large reductions in emissions could be achieved by widespread switching to renewable energy or nuclear power. However the extent to which those options might be used will be influenced by factors other than just their technical performance.

Capturing CO_2 and storing it underground can be done with available technology but it has only recently been seriously considered as a potential method of reducing emissions. Its importance stems from the fact that, currently, about 85% of the world's commercial energy needs are supplied by fossil fuels. A rapid change to non-fossil energy sources, even if possible, would result in large disruption to the energy supply infrastructure, with substantial consequences for the global economy. The technology of CO_2 capture and storage would enable the world to continue to use fossil fuels but with much reduced emissions of CO_2. In view of the many uncertainties about the course of climate change, further development of CO_2 capture and storage technologies is a prudent precautionary action.

The purpose of this report is to provide an overview of the technology for capture and underground storage of CO_2. It identifies the main opportunities for capturing CO_2 and describes how this would be done in practice. Transporting and storing CO_2 is then described. Some of the factors which will influence application, including environmental impact, cost and efficiency, are presented and, finally, the future prospects for the technology are discussed.

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 greenhouse gases. This helps to put in perspective the potential of capture and storage of CO_2.

WHERE CAN CO_2 BE CAPTURED?

Capture of CO_2 is best carried out at large point sources of emissions, such as power stations, which currently account for about a third of global CO_2 emissions. Other large point sources include oil refineries, petrochemical, fertiliser and gas processing plants, steel works and pulp and paper mills. This report will concentrate on large scale power generation but many of the points would also be applicable to the other major energy-using industries.

Capture in power generation

The main technologies used to generate power from fossil fuels are, currently, natural gas combined cycles and pulverised coal-fired steam cycles. Integrated Gasification Combined Cycles (IGCC) are also being developed, although they are generally considered to be not yet economically competitive. CO_2 capture could be incorporated in all of these types of plant. These technologies are described below. How they could be adapted to include CO_2 capture is described in the following section.

Pulverised coal-fired steam cycle

This has been the main power generation technology for more than 50 years. Pulverised coal is burned in a boiler which raises high pressure steam, which is then passed through a steam turbine, generating electricity. The efficiencies of modern coal fired power plant are around 40%. Plant with efficiencies of around 47%[1] have been built; such plant use higher steam temperatures and higher steam pressures. The key requirement in the development of higher efficiency steam cycle plant is the development of new materials (e.g. nickel and chromium alloys). Attempts are being made to develop materials for steam conditions up to 375bar/700°C, which would result in efficiencies of up to 55% at favourable Northern European coastal sites. Reaching these conditions may take up to 15 years.

An alternative to pulverised coal combustion is fluidised bed combustion. This is not discussed in detail in this report because the efficiencies, emissions and costs of fluidised bed combustion power plants are broadly similar to those of pulverised coal plants and the way in which CO_2 capture would be introduced is very similar.

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[1] On a lower heating value basis – this is used throughout this report.

Figure 2
A modern coal fired power station

(Courtesy of Elsam)

Natural gas combined cycle

Natural gas is burned in a gas turbine, which generates electricity. The hot exhaust gas from the gas turbine is fed to a boiler which generates steam, which is then passed through a steam turbine, generating more electricity. Natural gas combined cycles have been introduced mainly during the last 10 years, as the market for natural gas for power generation has become deregulated. World-wide, gas turbine based systems are taking well over half of the market for power plant. Large, commercial gas turbine combined cycle plant typically have thermal efficiencies of up to 56-58%. Within the next three years it is likely that efficiencies of 60% will be established as state-of-the-art and significantly higher efficiencies are expected to be achieved in future.

Figure 3
A natural gas combined cycle power station

(Courtesy of PowerGen)

IGCC

In this type of plant, fuel is reacted with oxygen and steam in a gasifier to produce a fuel gas consisting mainly of carbon monoxide and hydrogen. This is then cleaned and burned to generate power in a gas turbine combined cycle. The IGCC concept enables the use of fuels such as residual oil and coal in plant with the high efficiencies of a combined cycle; it also results in very low emissions of pollutants such as sulphur dioxide. The efficiencies of IGCC plants will increase in future in line with those of gas turbine combined cycles but IGCC plants are likely to be less efficient, by about 10 percentage points, because of the energy losses associated with gasification and gas cleaning.

The components of IGCC have been developed over many years. Gasifiers were first used in Germany immediately prior to World War II and were further developed in South Africa in the early 1980s. Over 300 gasifiers are reported to be in operation but most of these are producers of synthesis gas (CO, hydrogen and CO_2 mixtures) as an intermediate stage in chemicals production. Commercial-scale coal IGCC demonstration plants have been built in the USA, Netherlands and Spain. There is also a major interest in the oil industry in gasification of refinery residues to produce electricity and/or hydrogen and three large plants are being built in Italy. IGCC has been successfully demonstrated but the capital cost needs to be reduced and the reliability and operating flexibility needs to be improved to make it widely competitive in the electricity market.

Other Opportunities for CO_2 Capture

Major energy using industries

Four major industries account for about three quarters of total industrial CO_2 emissions, equivalent to about half of the emissions from power generation (Table 1 shows data for 1994-1996). These industries may present further opportunities for capturing CO_2 for storage. Aluminium production is another major energy using industry but most of its CO_2 emissions (over 300 million tonnes/y) arise from the generation of the electricity used by this industry.

About two thirds of the CO_2 emissions from oil refineries come from fired heaters. The flue gas from these heaters is similar to the flue gas in power stations, so CO_2 could be captured using the same techniques and at broadly similar costs. About 60% of the CO_2 emitted by the iron and steel industry is in the off-gas from blast furnaces; both this and the newer direct reduction processes would be suitable applications for CO_2 capture. CO_2 emitted in the flue gases from cement production could also be captured using similar techniques. Flue gases at large point sources in other industries may also be suitable for CO_2 capture

Table 1
CO_2 emissions by major industries
Sources: IEA GHG (individual industries), OECD Environmental Data 1997 (overall), IEA World Energy Outlook 1998 (power generation).

	CO_2 emissions Million tonnes/year
Iron and steel production	1440
Cement manufacture	1130
Oil refining	690
Petrochemicals	520
Other industry	1320
Overall industry	5100
Power generation	7660

In some other industries, for example production of hydrogen for ammonia, fertilisers and processing of natural gas, CO_2 is already being separated. Most of this CO_2 is vented to the atmosphere but it could be stored underground at little extra cost. This could provide useful opportunities to demonstrate the feasibility of CO_2 transport and storage, as well as early application as a mitigation technique. The first example of this being done on a commercial scale is the Sleipner Vest gas field in the Norwegian sector of the North Sea, where CO_2 separated from natural gas is injected into an underground saline reservoir.

Figure 4
Oil and gas production facilities, in the Sleipner field

(Courtesy of Statoil)

Energy carriers for distributed energy users

A large amount of fossil fuel is used in transport, e.g. cars or aircraft, and in small-scale heat or power production. It is not practicable to capture, collect, and store CO_2 from such sources using current technologies. Nevertheless, large reductions could be made in CO_2 emissions from these dispersed sources, through use of a carbon-free energy carrier, such as hydrogen. Hydrogen is often considered as a carrier for energy from renewable sources. However, it can also be produced from fossil fuels, using capture and storage technology to minimise release of CO_2. Production of hydrogen from fossil fuels with CO_2 storage could be an attractive transitional strategy to aid the introduction of hydrogen as an energy carrier.

HOW CAN CO_2 BE CAPTURED?

There are two basic options for capture of CO_2 in power stations: post-combustion or pre-combustion.

Post-combustion capture

CO_2 is only a small part of the flue gas stream emitted to atmosphere by a power station (Table 2). Other gases include nitrogen, oxygen and water vapour. It would be impractical to store flue gases underground because there would be insufficient storage space and because too much energy would be needed to compress the flue gas. Some method of separation is therefore required to capture the CO_2.

Table 2
CO_2 concentration in power station flue gas

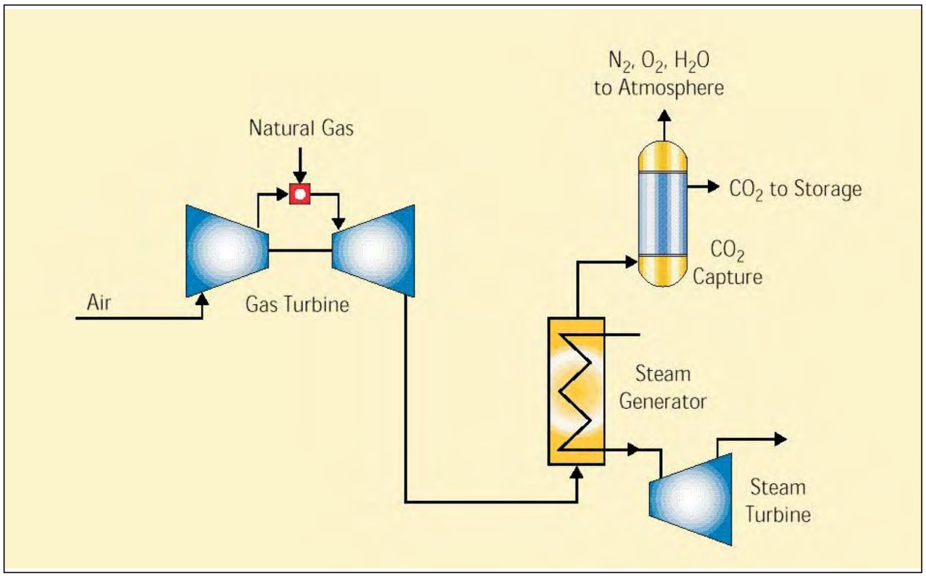
	CO_2 concentration in flue gas vol %, approx.)
Pulverised coal fired	14
Coal fired IGCC	9
Natural gas combined cycle	4

CO_2 can be captured using technologies that have been developed and proved in other applications.

A variety of techniques are available - the main one in use today for separating CO_2 from flue gases or other gas streams is scrubbing the gas stream using an amine solution. After leaving the scrubber, the amine is heated to release high purity CO_2 and the CO_2-free amine is then reused. Figure 5 is a simplified diagram of a gas turbine combined cycle power station with post-combustion capture of CO_2. Such techniques can also be applied to coal fired power stations but with some additional cleaning of the flue gases. In many respects, post-combustion capture of CO_2 is analogous to flue gas desulphurisation (FGD), which is widely used on coal- and oil-fired power stations to reduce emissions of SO_2.

The low concentration of CO_2 in flue gas means that a large volume of gas has to be handled, resulting in large and expensive equipment. A further disadvantage of the low CO_2 concentration is that powerful solvents have to be used to capture CO_2 - regeneration of these solvents, to release the CO_2, requires a large amount of energy. The CO_2 concentration can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or gas turbine. If fuel is burnt in pure oxygen, the flame temperature is excessively high, so some CO_2-rich flue gas would be recycled to the combustor to make the flame temperature similar to that in a normal combustor. The advantage of oxygen-blown combustion is that the flue gas has a CO_2 concentration of typically >90%, so only simple CO_2 purification is required. The disadvantage is that production of oxygen is expensive, both in terms of capital cost and energy consumption.

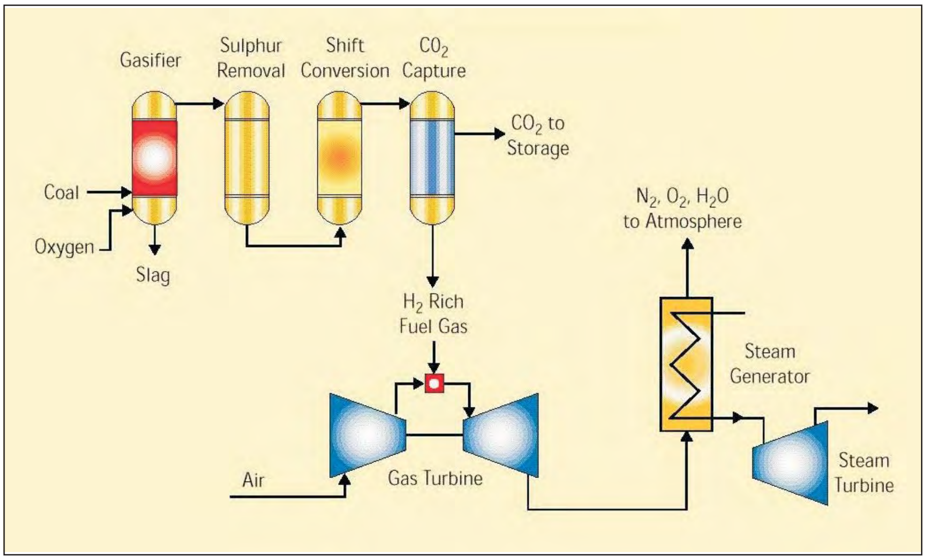
Figure 5
Gas turbine combined cycle with post-combustion capture of CO_2



Pre-combustion capture

An alternative way to increase the CO_2 concentration and partial pressure is to use pre-combustion capture. This involves reacting the fuel with oxygen and/or steam to give mainly carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is then separated and the hydrogen is used as fuel in a gas turbine combined cycle plant. The process is, in principle, the same for coal, oil or natural gas. Figure 6 is a simplified diagram of a coal-fired power plant with pre-combustion capture of CO_2.

Figure 6
Coal fired IGCC with pre-combustion capture of CO_2



Although pre-combustion capture involves a more radical change to the power station design, most of the technology is already well proven in ammonia production and other industrial processes. One of the novel aspects is that the fuel gas is essentially hydrogen. It is expected that it will be possible to burn hydrogen in an existing gas turbine with little modification but this is not commercially proven technology. At least two gas turbine manufacturers are known to have undertaken tests on combustion of hydrogen-rich fuels.

The hydrogen produced in pre-combustion capture processes could, alternatively, be used to generate electricity in a fuel cell. The technology of capture and storage is therefore expected to be suitable for future as well as current power generation technologies.

CO_2 capture technologies

Solvent scrubbing

Amine scrubbing technology was established over 60 years ago in the oil and chemical industries, for removal of hydrogen sulphide and CO_2 from gas streams. Commercially, it is the most well established of the techniques available for CO_2 capture although practical experience is mainly in gas streams which are chemically reducing, the opposite of the oxidising environment of a flue gas stream. There are several facilities in which amines are used to capture CO_2 from flue gas streams today, one example being the Warrior Run coal fired power station in the USA, shown in Figure 7, where 150 t/d of CO_2 is captured.

Figure 7
CO_2 capture plant at Warrior Run power station, Cumberland, USA

(Courtesy of AES)

Mono-ethanolamine (MEA) is a widely used type of amine for CO_2 capture. CO_2 recovery rates of 98% and product purity in excess of 99% can be achieved. There are, however, questions about its rate of degradation in the oxidising environment of a flue gas and the amount of energy required for regeneration. Improved solvents could reduce energy requirements by as much as 40% compared to conventional MEA solvents. There is considerable interest in the use of sterically-hindered amines which are claimed to have good absorption and desorption characteristics.

The conditions for CO_2 separation in pre-combustion capture processes will be quite different from those in post-combustion capture. For example, in a coal

IGCC process, modified for capture, the CO_2 concentration would be about 35-40% at a pressure of 20 bar or more. In that case, physical solvents, such as Selexol®, could be used for pre-combustion capture of CO_2, with the advantage that the CO_2 can be released mainly by depressurisation, thereby avoiding the high heat consumption of amine scrubbing processes. However, depressurisation of the solvent still results in a significant energy penalty. Physical solvent scrubbing of CO_2 is well established, e.g. in ammonia production.

Cryogenics

CO_2 can be separated from other gases by cooling and condensation. Cryogenic separation is widely used commercially for streams that already have high CO_2 concentrations (typically >90%) but it is not used for more dilute CO_2 streams. A major disadvantage of cryogenic separation of CO_2 is the amount of energy required to provide the refrigeration necessary for the process, particularly for dilute gas streams. Another disadvantage is that some components, such as water, have to be removed before the gas stream is cooled, to avoid blockages. Cryogenic separation has the advantage that it enables direct production of liquid CO_2, which is needed for certain transport options, such as transport by ship. Cryogenics would normally only be applied to high concentration, high pressure gases, such as in pre-combustion capture processes or oxygen fired combustion.

Membranes

Gas separation membranes allow one component in a gas stream to pass through faster than the others. There are many different types of gas separation membrane, including porous inorganic membranes, palladium membranes, polymeric membranes and zeolites. Membranes cannot usually achieve high degrees of separation, so multiple stages and/or recycle of one of the streams is necessary. This leads to increased complexity, energy consumption and costs. Several membranes with different characteristics may be required to separate high-purity CO_2. Solvent assisted membranes are being developed to combine the best features of membranes and solvent scrubbing. Much development is required before membranes could be used on a large scale for capture in power stations.

Adsorption

Solid adsorbents, such as zeolites and activated carbon, can be used to separate CO_2 from gas mixtures. In pressure swing adsorption (PSA), the gas mixture flows through a packed bed of adsorbent at elevated pressure until the concentration of the desired gas approaches equilibrium. The bed is regenerated by reducing the pressure. In temperature swing adsorption (TSA), the adsorbent is regenerated by raising its temperature. PSA and TSA are commercially practiced methods of gas separation and are used to some extent in hydrogen production and in removal of CO_2 from natural gas. Adsorption is not yet considered attractive for large-scale separation of CO_2 from flue gas because the capacity and CO_2 selectivity of available adsorbents is low. However, it may be successful in combination with another capture technology.

TRANSPORT OF CO_2

After capture, CO_2 would be transported to the storage site. CO_2 is largely inert and easily handled and it is already transported in high pressure pipelines. About 30 million tonnes/year of CO_2 is currently transported by pipeline in the USA. The longest pipeline at present is the Sheep Mountain pipeline, which is 656 km long. If CO_2 capture and storage became widely used, pipeline grids such as those used for natural gas distribution would probably be built, to improve operating flexibility and provide economies of scale.

Ships would be used for long distance transport of CO_2. Although CO_2 is not transported by ship at present, tankers similar to those currently used for liquefied petroleum gas (LPG), shown in Figure 8, could be used.

Figure 8
An LPG tanker - CO_2 could be transported in a similar way

(Courtesy of Mitsubishi Heavy Industries Ltd.)

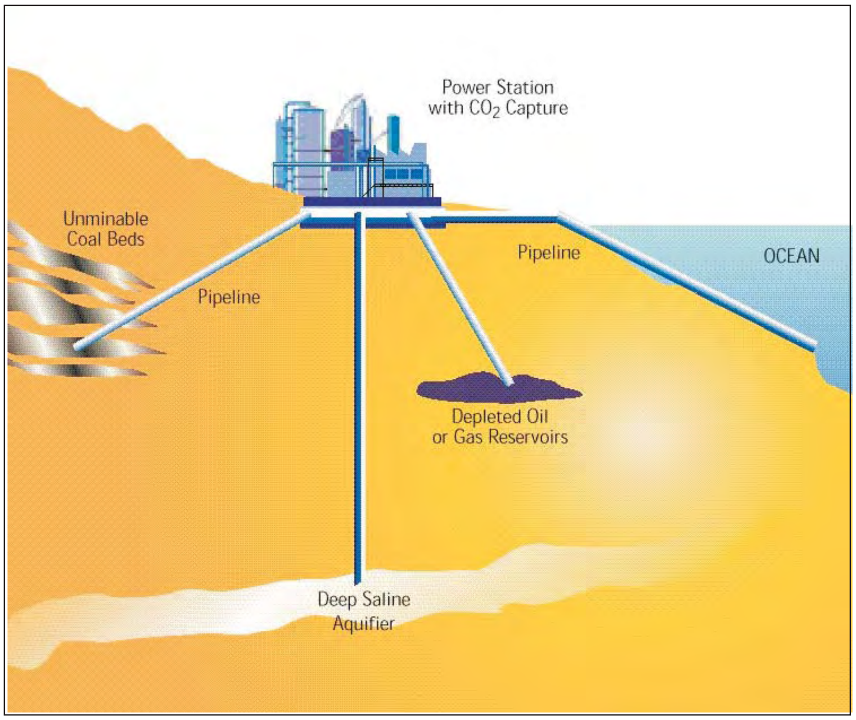
At high concentrations, CO_2 is an asphyxiant and, because it is heavier than air, it will tend to collect in depressions. The risks of problems due to pipe leakage are very small but, to minimise risks, CO_2 pipelines could be routed away from large centres of population. Some intermediate storage of CO_2 will be needed to cope with variability in supply, transport and storage, particularly if CO_2 is transported by ship. Other potentially hazardous gases such as natural gas, ethylene and LPG are already stored, with very few problems. The same safety considerations would need to be applied to intermediate storage of CO_2.

It is typically cheaper to pipe CO_2 than to transmit electricity. It would therefore be cheaper to locate power stations close to electricity demand and transport the CO_2 as necessary to the storage site. However, if transport of CO_2 is a major concern, power stations could be built close to the storage sites.

UNDERGROUND STORAGE OF CO_2

For CO_2 storage to be an effective way of avoiding climate change, the CO_2 must be stored for several hundreds or thousands of years. CO_2 storage also needs to have low environmental impact, low cost and conform to national and international laws. The main options for storing CO_2 underground are in depleted oil and gas reservoirs, deep saline reservoirs and unminable coal seams, as shown in Figure 9. Storage of CO_2 in the deep ocean has also been proposed; this is summarised in another report by IEA GHG (see bibliography)

Figure 9
Options for storage of CO_2



Depleted oil and gas reservoirs

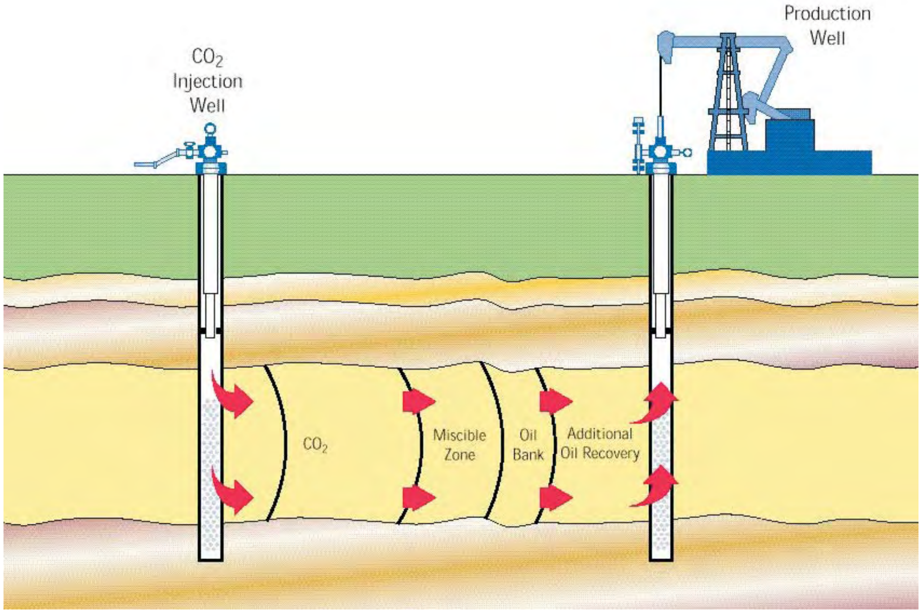
Oil and gas reservoirs consist of porous rocks covered by impermeable cap rock, which is often dome shaped. Following more than a century of intensive petroleum exploitation, thousands of oil and gas fields are approaching the ends of their economically productive lives. Some of these depleted fields could act as effective storage sites for CO_2.

Depleted oil and gas fields have a number of attractive features as CO_2 storage reservoirs:

- Exploration costs would be small
- The reservoirs are proven traps, known to have held liquids and gases for millions of years
- The reservoirs have well known geology
- There is potential to re-use some parts of the hydrocarbon production equipment to transport and inject the CO_2.

In most oil fields only a portion of the original oil in place is recovered using standard petroleum extraction methods. CO_2 injected into suitable, depleted oil reservoirs can enhance oil recovery by typically 10-15% of the original oil in place in the reservoir. This is an established technique, called CO_2-EOR (enhanced oil recovery), which is illustrated in Figure 10. The additional oil production could, in certain circumstances, more than offset the cost of CO_2 capture and injection.

Figure 10
CO_2 enhanced oil recovery



About 33 million t/y of CO_2 is already used at more than 74 EOR projects in the USA - most of this CO_2 is extracted from natural reservoirs but some is captured, as described above, from natural gas plants and ammonia production. A further 6 million t/y of CO_2 has been injected as part of a large CO_2-EOR project in Turkey. An example of a CO_2-EOR scheme using anthropogenic CO_2 is the Weyburn project in Canada. CO_2 captured in a large coal gasification project in North Dakota, USA is to be transported 200 miles by pipeline and injected into the Weyburn field in Saskatchewan. Initially 5 000 tonnes per day of CO_2 will be injected. An international research project, organised through the IEA Greenhouse Gas R&D Programme, will aim to determine how effective this CO_2 storage will be over the long term.

Depleted natural gas fields are also feasible sites for CO_2 storage. Underground storage in natural reservoirs has been an integral part of the natural gas industry for many decades. Natural gas is routinely injected into, stored and withdrawn from hundreds of underground storage fields. Some depleted gas fields could be adapted easily for storage of CO_2.

Figure 11
Weyburn CO_2 EOR project

(Courtesy of Saskatchewan Energy and Mines)

There will need to be some changes in current practice in order to make use of depleted oil and gas reservoirs for CO_2 storage. For example, operational procedures for EOR with CO_2 storage may differ significantly from current EOR schemes. Transfer of ownership of a depleted field from the licensed operator to a storage operator is, as yet, an untried procedure. Also, abandoned fields will still contain oil and gas resources, which potentially have economic value if oil prices were to rise enough or new EOR technologies were developed in future. All of these aspects will be need to be addressed in order to make use of depleted oil and gas fields for CO_2 storage.

Deep saline reservoirs

There are many underground, water-filled strata (aquifers) that could potentially be used to store CO_2. The aquifers that would be used for CO_2 storage are deep underground, contain saline water and are unsuitable for supplying potable water. CO_2 would partially dissolve in the water in the aquifer and in some formations it would slowly react with minerals to form carbonates, which would lock up the CO_2 essentially permanently. Suitable aquifers would have a cap rock of low permeability to minimise CO_2 leakage. Injection of CO_2 into deep saline reservoirs would use techniques similar to those for disused oil and gas fields.

Nearly a million tonnes per year of CO_2 is already being injected into a deep saline reservoir under the Norwegian sector of the North Sea in conjunction with gas production from the Sleipner Vest gas field. When this injection began in 1996 it marked the first instance of CO_2 being stored in a geological formation because of climate change considerations.

CO_2 removed from a natural gas stream, which would normally be discharged to the atmosphere, is being stored underground. The storage reservoir is the Utsira formation, which is a sand formation extending under a large area of the North Sea at a depth of about 800m. The flows of CO_2 injected at Sleipner are being monitored and modelled as part of an international project established by Statoil with the IEA Greenhouse Gas R&D Programme. This work should help in the design and operation of future CO_2 injection projects.

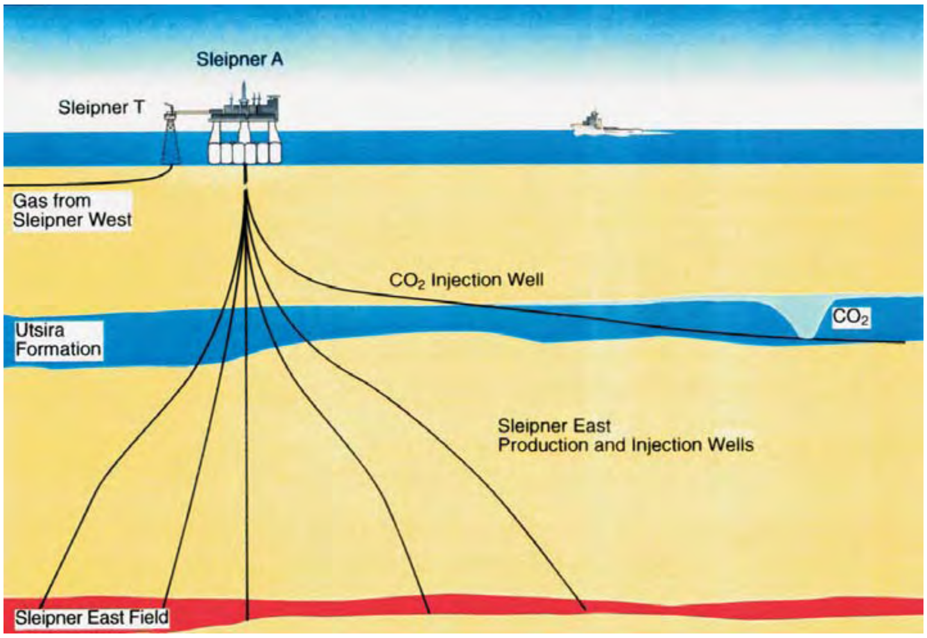


Figure 12
CO_2 injection into the Utsira deep saline reservoir

(Courtesy of Statoil)

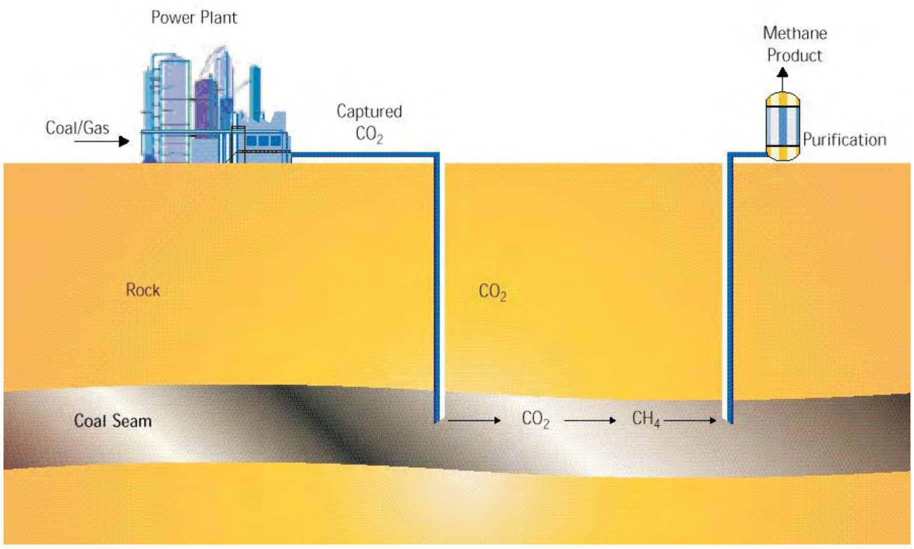
Unminable coal seams

Another potential storage medium is unminable coal. CO_2 can be injected into suitable coal seams where it will be adsorbed onto the coal, locking it up permanently provided the coal is never mined. Moreover, it preferentially displaces methane that exists in the coal. Methane is already extracted from coal seams by depressurisation but this typically recovers only about 50% of the gas in place. Injection of CO_2 enables more methane to be extracted, while at the same time sequestering CO_2. Coal can adsorb about twice as much CO_2 by volume as methane, so even if the recovered methane is burned and the resulting CO_2 is reinjected, the coal bed can still provide net storage of CO_2.

A substantial amount of coal bed methane is already produced in the USA and elsewhere but, so far, there is only one CO_2-enhanced coal bed methane project, the Allison Unit in New Mexico, USA. Over 100 000 tonnes of CO_2 has been injected at this unit over a three year period.

A field test of enhanced coal bed methane (ECBM) production using CO_2 and nitrogen mixtures is being carried out by the Alberta Research Council under an international project facilitated by the IEA Greenhouse Gas R&D Programme. The combined approach may offer more attractive means of recovering methane and storing CO_2.

Figure 13
CO_2 enhanced coal bed methane production



Other storage options

There are various other ways of potentially storing CO_2 but none has been found to be economically competitive against the options described above. Underground caverns, such as mined salt domes, could be created to store CO_2. Such caverns are used for short term storage of natural gas and certain industrial gases but the quantities of CO_2 that would need to be stored are very much larger. Solid CO_2 (dry ice) could also be stored in a repository, surrounded by thermal insulation to minimise heat transfer and loss of CO_2 gas.

Another option is to react CO_2 with naturally occurring minerals, such as magnesium silicate, to produce carbonates that could be stored permanently. However, the mass of mineral that would need to be quarried and stored would be substantially more than the mass of CO_2 and costs would be much higher than for storage in oil and gas reservoirs, aquifers and coal seams. An advantage of this option is that the CO_2 would be locked-up for extremely long timescales. However, a better way to achieve this end may be to inject CO_2 into underground reservoirs that contain minerals that will react with CO_2.

Storage capacities

The global potentials for underground CO_2 storage, estimated by the IEA Greenhouse Gas R&D Programme, are shown in Table 3. These numbers may be compared with projected total emissions between 2000 and 2050, according to a “business as usual” scenario (the IPCC’s IS92a projection), which shows that this technique could have a substantial impact on CO_2 emissions.

Table 3
Natural reservoirs suitable for storage of CO_2

Storage option	Global capacity	
	Gt CO_2	% of emissions to 2050
Depleted oil and gas fields	920	45
Deep saline reservoirs	400 - 10 000	20-500
Unminable coal measures	>15	>1

The estimates for deep saline reservoirs were made in the early 1990s. More recent estimates suggest the capacity for storage in geological reservoirs in North West Europe alone could be as much as 800 Gt CO_2 (most of this is in deep saline reservoirs). Further research is required to assess the potential storage capacity of deep saline reservoirs.

ENVIRONMENTAL IMPACTS

Much of the technology for transportation and storage of gases is established and in use today. Large quantities of CO_2 are routinely transported in pipelines and tankers. CO_2 is injected underground in many EOR projects. Underground storage of natural gas, an analogous technique, is widely practised. This gives confidence that the new concept of underground storage for sequestration of CO_2 can be done in a safe and reliable manner.

Nevertheless, because CO_2 is an asphyxiant and heavier than air, there may be concerns about the safety of underground storage - either possible slow leakage or sudden large-scale emission resulting from seismic activity. Slow leakage of CO_2 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 ways as for other gases, such as by avoiding unsuitable sites. It is also important that CO_2 remains in the underground stores for a long enough time to minimise climate change. Oil and gas fields have remained secure for millions of years but there is a possibility that drilling and extraction of oil and gas may disrupt the integrity of the cap. Chemical interactions between injected CO_2 and underground minerals would have the beneficial effect of permanently sequestering CO_2 but there is a possibility that interactions could impact the integrity of the cap rock. Deep saline reservoirs are generally less well characterised than oil and gas reservoirs due to their lack of commercial importance to date. More information is needed to calibrate their ability to contain CO_2 for the necessary timescales.

Solvents used to capture CO_2 gradually degrade in use and so there need to be suitable procedures for destruction/disposal. There may also be some solvent carry-over in the flue gas stream. Both of these factors will be minimised for cost reasons, as well as to reduce potential environmental impacts. It has been suggested that the CO_2 capture at a 500 MW gas-fired power station could produce about 2 000 tonnes/year of sludge from decomposed amines, and about 10 tonnes/year of carry-over in the flue gas. However, these quantities are speculative and are the subject of further evaluation.

Possible legal and political obstacles to storage of CO_2 will need to be addressed. For example, the London Convention may in some circumstances limit the opportunities for storage of CO_2 under the sea bed. However, storage of CO_2 to mitigate climate change was not considered at the time the Convention was agreed.

VERIFICATION OF CO_2 STORAGE

If CO_2 storage were to be used as a basis for emissions trading or to meet national commitments on emissions reduction, it would be necessary to verify the quantities of CO_2 stored. Verification is also a significant challenge for other carbon storage options, such as forestry and enhanced storage in soils.

For CO_2 capture, the flows of gas would be measured as a normal part of the chemical engineering of the process; technology already exists to do this and additional costs would be small. Capture of flue gases can be measured with great accuracy and at low cost. Also, with transport of CO_2, pipelines already carry CO_2 across the USA on a commercial scale, with large quantities of CO_2 monitored accurately in real time using equipment that is available now at low cost. Similar measurements would be used to monitor CO_2 injected into geological reservoirs.

Major oil and gas companies and their contractors have the technology to track gas flows in underground reservoirs using seismic, well logging, and reservoir simulation tools. These technologies are being successfully applied in EOR projects and in the North Sea. Logging technology would be most easily applied in reservoirs where there are also production wells (e.g. oil production). The application to, and effectiveness of, seismic technology for tracking stored CO_2 in underground reservoirs is showing promise, but further development of the technique is required. Tracking will need to be accurate over much longer periods of time for CO_2 storage compared to EOR, where slow leakage is not a major concern.

PERFORMANCE AND COSTS

Power generation efficiency and emissions

The IEA Greenhouse Gas R&D Programme has recently completed a study on the performance and cost of new 500 MW_e (nominal) gas and coal fired power plants with and without CO_2 capture. Power stations with post-combustion capture using amine scrubbing, and pre-combustion capture using Selexol® physical solvent scrubbing were assessed. The coal IGCC uses pre-combustion capture and the pulverised coal and natural gas combined cycle plants use post-combustion capture (the efficiency and emissions would be very similar for a natural gas combined cycle with pre-combustion capture). Compression of the CO_2 to a pressure of 110 bar for transportation to storage is included.

The efficiencies and emissions of power stations with and without CO_2 capture are shown in Figures 14 and 15.

Figure 14
Power generation efficiencies

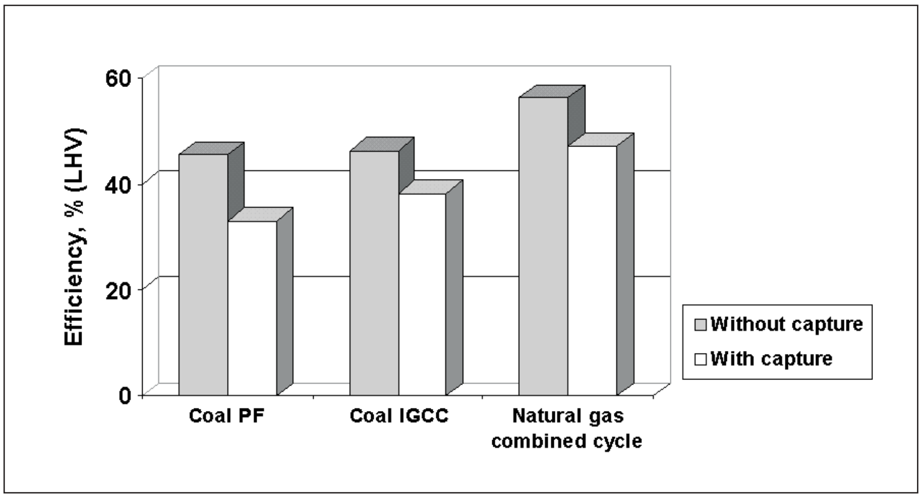
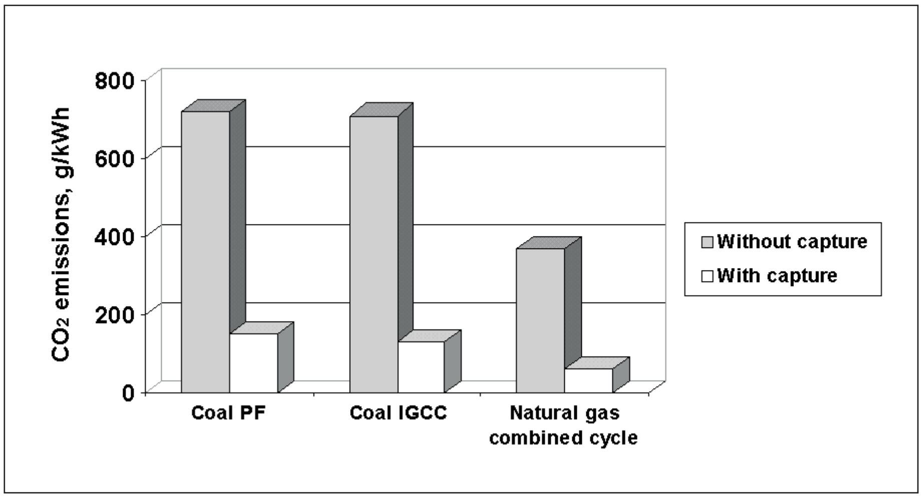


Figure 15
Power station CO_2 emissions



CO_2 capture reduces the emissions of CO_2 per unit of electricity by about 80%. The generating efficiency decreases by 8-13 percentage points. The reduction in efficiency is less in the gas fired plant than in the pulverised coal plant, mainly because less CO_2 has to be captured and compressed per unit of electricity produced. The efficiency penalty for CO_2 capture is lower in the IGCC plant than in the pulverised coal plant, because less energy is needed for regeneration of the CO_2 capture solvent .

Power generation costs

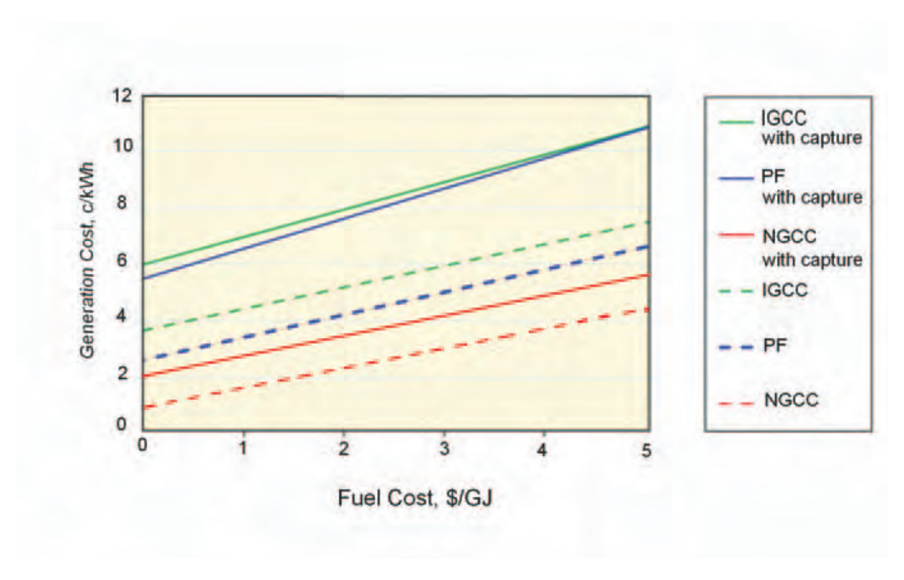
Capital and operating costs of power stations with and without CO_2 capture were estimated to an accuracy of ±25%. Adding CO_2 capture approximately doubles the capital cost of a natural gas combined cycle plant. CO_2 capture increases the capital cost of a pulverised coal plant by 80% and an IGCC plant by 50%, although even with CO_2 capture the IGCC plant is still more expensive than the pulverised coal plant.

The costs of transport and storage of compressed CO_2 is expected to be low compared to the costs of capture and compression. The IEA Greenhouse Gas R&D Programme, has estimated that storage in deep saline reservoirs and in depleted oil and gas fields would cost \$1-3/t CO_2, excluding the cost of CO_2 transport. In some cases injection of CO_2 e.g. in enhanced oil recovery or enhanced production of coal bed methane, will generate an income which can partially offset the cost of capture and storage. Local conditions will dictate how far the CO_2 has to be transported from where it is produced to where it is stored. The cost of pipeline transport is estimated to be ~\$1-3/t CO_2 for 100km distance.

Cost of electricity

Costs of electricity generation with and without CO_2 capture and storage at a range of fuel prices are shown in Figure 16. The costs are calculated assuming a 10% discount rate, base load operation and a CO_2 transport and storage cost of \$8/t CO_2 stored.

Figure 16
Costs of electricity generation with and without CO_2 capture and storage

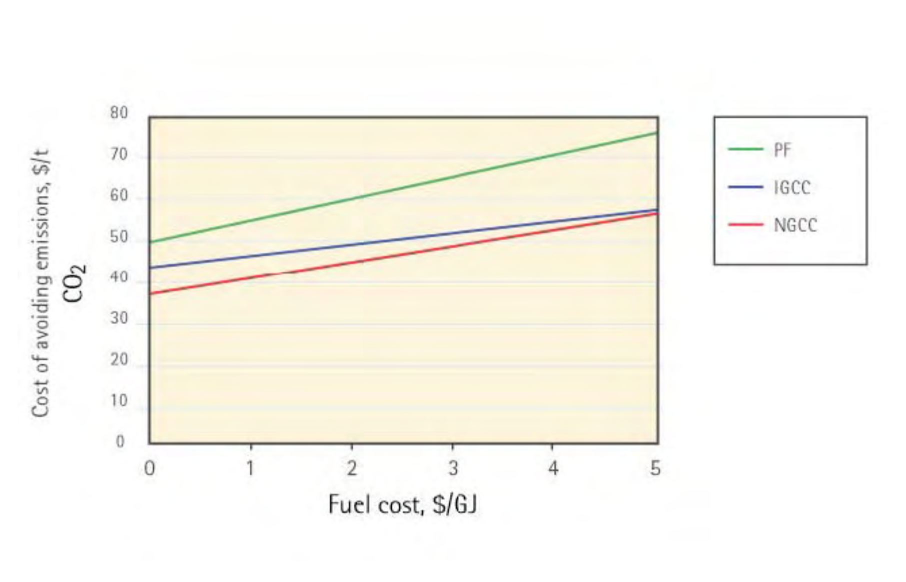


CO_2 capture and storage increases the cost of gas fired electricity generation by about 1.5 c/kWh, or 60%. Post-combustion CO_2 capture and storage increases the cost of electricity generation in a pulverised coal plant by about 3 c/kWh or 90%. The cost of electricity from an IGCC with pre-combustion capture is roughly the same as from a pulverised coal plant with post combustion capture. In percentage terms, the increase in cost of electricity to the final consumer would be less because of the added costs of distribution and sales.

Cost of avoiding CO_2 emissions

The cost of avoiding CO_2 emissions at a range of fuel costs is shown in Figure 17 (the cost is assessed relative to a similar plant without capture).

Figure 17
Costs of avoidingCO_2 emissions



The overall cost is around \$40-60/t CO_2 emissions avoided and is broadly similar for coal and gas fired power plants. The quantity of CO_2 emissions *avoided* is less than the quantity *captured*, because the energy consumed during capture results in additional CO_2 production. The cost per tonne of CO_2 *captured* would therefore be lower than the cost per tonne of emissions avoided.

Other industries

As indicated above, CO_2 is already separated during some petrochemical and gas purification processes. The cost of capturing and storing this CO_2 would be low, as it would only have to be pressurised and in some cases some minor impurities removed. This suggests that such plant may offer opportunities for early action and some projects have already been proposed. CO_2 could also be captured in other major energy using industries, as discussed earlier. Costs per tonne of CO_2 are expected to be broadly similar to those of power plants.

Future cost trends

As with most new technologies, costs of CO_2 capture and storage are expected to decrease when they are applied on a large scale and technical improvements are made. The analogous situation occurred with FGD. Capital costs of FGD plants have decreased by about 75% since they were first introduced on a large scale around 1970. FGD was originally regarded as an excessively expensive addition to power stations but is now usually regarded as a relatively modest addition, fully justified by the environmental benefits.

FUTURE PROSPECTS

Market opportunities

Markets for CO_2 capture and storage technology will depend on future energy demand, the degree of CO_2 emission-abatement required and its relative attractiveness compared with other abatement options. The main application for capture and storage in the long term would be power generation but, near term, there may be opportunities for emission reduction from other sources. Although these may not have the potential global benefit of the power sector, they would be less costly to build. Application in projects which can generate some offsetting income is also expected to be attractive, especially near term.

About 100 GW_e per year of new fossil fuel fired power plant is currently being ordered worldwide, 70% of which is gas fired. The market for power plant is likely to grow at 2-3% for the foreseeable future. A substantial proportion of new power plant could potentially include CO_2 capture and storage. Retrofitting to existing plants is feasible but would require large modifications, necessitating a long operating life to recover the capital investment. Major energy using industries are another major potential application for capture and storage and adoption of this technology to produce energy carriers such as hydrogen could open up much of the rest of the energy market to deep reductions in CO_2 emissions.

Research and development needs

The technology for capture and storage of CO_2 is already available, the main barriers to wider use being the energy penalty, cost of capture and the need to prove the reliability of storage and the integration of technologies at the required scale. This indicates areas of immediate priority for further development. Some specific topics are outlined below.

CO_2 capture:

The near-term priority is to reduce the penalty of using CO_2 capture in power plant. In the case of absorption technology there is scope for the development of improved solvents, starting at the laboratory scale and leading to use in commercial scale plants. Investigation of improved separation processes would also be justified, e.g. membranes, cryogenic separation, improved heat recovery to compensate for losses introduced by CO_2 capture, and novel concepts such as different methods of separating oxygen, enriched oxygen combustion or a combined reactor/membrane separator for the decarbonisation of fuel gases.

In the long-term, international agreement to reduce CO_2 emissions would likely alter the nature of the world’s energy systems; for example, it might accelerate the introduction of a hydrogen-based energy system. Initial distribution of hydrogen produced by decarbonising fossil fuels would provide a practicable ‘bridge’ to an energy system based primarily on non-fossil sources.

CO_2 storage:
The main requirement for research is to establish storage as an environmentally acceptable solution to the threat of climate change. The security of storage in a variety of applications needs to be demonstrated. Storage is less expensive than capture, so research to reduce costs is not a high priority.

Work under European and US programmes has identified and quantified potential underground stores but there is considerable need for more information on potential storage sites. Refinement of techniques to monitor CO_2 in underground strata will take place as part of the Sleipner and Weyburn projects and other programmes. Research to assess the long-term interaction of CO_2 with potential host rocks will be done in the laboratory. Before land-based schemes could be adopted (the only existing scheme is under the North Sea), their safety and public acceptability would need to be established.

Other matters:
It is important to involve a wide range of interest groups in considering the environmental and social issues related to many new technologies, including CO_2 capture and storage. The views of environmental non-governmental organisations (ENGOs), industry, government agencies, lawyers and others are needed, as well as those of scientists and researchers, to identify areas of concern and agree the main research needs.

There are significant advantages in many cases if R&D is undertaken by international co-operation. These opportunities also apply to potential demonstration projects where the need to focus limited resources and the high costs make international co-operation highly desirable.

Formal recognition of CO_2 capture and storage within the UNFCCC would contribute to faster development and take-up.

CONCLUSIONS

Large reductions in emissions of CO_2 to the atmosphere are likely to be needed to avoid major climate change. Capture and storage of CO_2, in combination with other CO_2 abatement techniques, could enable these large reductions to be achieved with least impact on the global energy infrastructure and the economy.

Capture and storage is particularly well suited to use in central power generation and many energy-intensive industrial processes. CO_2 capture and storage technology also provides a means of introducing hydrogen as an energy carrier for distributed and mobile energy users.

CO_2 can be captured using available technology. Potential stores for CO_2, e.g. natural underground reservoirs, have sufficient capacity for many years' emissions.

The environmental side-effects of CO_2 capture and storage are mostly quite small.

For power stations, the cost of capture and storage is about $50/t of CO_2 avoided. This compares favourably with the cost of many other options considered for achieving large reductions in emissions. Use of this technique would allow continued provision of large-scale energy supplies using the established energy infrastructure.

There is considerable scope for new ideas to reduce energy consumption and costs of CO_2 capture and storage which would accelerate the development and introduction of this technology.

BIBLIOGRAPHY

Department of Trade and Industry (UK), *Gasification of Solid and Liquid Fuels for Power Generation*, report TSR 008, Dec. 1998

Department of Trade and Industry (UK), *Supercritical Steam Cycles for Power Generation Applications*, report TSR 009, Jan. 1999

Durie R, Paulson C, Smith A and Williams D, P*roceedings of the 5th International Conference on Greenhouse Gas Control Technologies, CSIRO (Australia) publications*, 2000

Eliasson B, Riemer P W F and Wokaun A (editors), *Greenhouse Gas Control Technologies, Proceedings of the 4th International Conference,* Elsevier Science Ltd., Oxford 1999

Herzog H, Eliasson B and Kaarstad O, *Capturing Greenhouse Gases*, Scientific American, Feb. 2000, 54-61

Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995 - The Science of Climate Change*, Cambridge University Press, 1996

International Energy Agency, *Key World Energy Statistics*, 1999 edition.

IEA Greenhouse Gas R&D Programme, *Transport & Environmental Aspects of Carbon Dioxide Sequestration*, 1995, ISBN 1 898373 22 1

IEA Greenhouse Gas R&D Programme, *Abatement of Methane Emissions*, June 1998, ISBN 1 898 373 16 7

IEA Greenhouse Gas R&D Programme, *Ocean Storage of* CO_2, Feb. 1999, ISBN 1 898 373 25 6

IEA Greenhouse Gas R&D Programme, *The Reduction of Greenhouse Gas Emissions from the Cement Industry*, report PH3/7, May 1999

IEA Greenhouse Gas R&D Programme, *The Reduction of Greenhouse Gas Emissions from the Oil Refining and Petrochemical Industry*, report PH3/8, June 1999

IEA Greenhouse Gas R&D Programme, *Leading Options for the Capture of* CO_2 *Emissions at Power Stations*, report PH3/14, Feb. 2000

Stevens S and Gale J, *Geologic* CO_2 *Sequestration*, Oil and Gas Journal, 15 May 2000, 40-44

US Department of Energy, Office of Science, Office of Fossil Energy, *Carbon Sequestration Research and Development*, December 1999, www.ornl.gov/carbon_sequestration/