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Sustainable Development and

CO_2 Capture and Storage

A report for UN Department of Economic and Social Affairs

Prepared by Dr Paul Freund

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Executive Summary

The threat of climate change and the importance of fossil fuels in global energy supply have recently stimulated much interest in CO_2 capture and storage (CCS). The most important application of CO_2 capture would be in power generation, the sector which is responsible for 75% of global CO_2 emissions from large stationary industrial sources.

Two options for capture are based on well established technology - post-combustion capture using chemical solvent scrubbing would be used in current designs of power stations; pre-combustion capture using physical solvent separation involves a small modification to the design of gasification based systems which are increasingly being considered for future power plants. A third approach, oxyfuel combustion, has not yet been demonstrated at full scale but several pilot plants are under construction. Captured CO_2 would be transported by pipeline to storage in geological formations – this might be in disused oil or gas fields or in deep saline aquifers. Use of the CO_2 to enhance oil or gas production offers the possibility of generating some income to offset part of the cost of CCS.

CCS increases the energy used for power generation by about 25-50% and reduces emissions by about 85%. The levelized cost of electricity generation would be increased by between 40% and 90% depending on the design of the plant and type of fuel. There is sufficient capacity worldwide for CO_2 storage to make a substantial contribution to reducing global emissions, although the capacity is not distributed evenly. Economic modelling shows that use of CCS would significantly reduce the cost of meeting the goal of stabilizing atmospheric concentrations of CO_2, especially at levels of 450 - 550 ppmv.

Means of financing and methods of regulation are under development. Recent decisions by the London and OSPAR Conventions have removed a legal obstacle to CO_2 storage in sub-seabed formations. Monitoring and verification requirements will be dictated by the needs of the regulators, amongst other things, and have yet to be fully defined. Risk assessment will be important for gaining

approval for CCS projects. Decisions about who has responsibility for any future liability will be needed before storage is widely deployed. Public attitudes will also be important but as yet CCS is not widely known or understood by the public as a mitigation option.

Commercial projects are being announced at an increasing pace, albeit with reservations about when the CCS component will be installed. No full-scale CCS-equipped power plants are in use at present but 8 projects appear to have good prospects of being constructed in the near future, together with several pilot plants. Plans for another 29 full-scale power plant installations have been announced in Europe, North America and Australia but their use of CCS depends on there being a suitable financial and regulatory climate.

Future financing for projects in Annex 1 countries will depend on developments in emissions trading schemes. CCS is not acceptable for CDM funding at present but this may change within 2 years if the concerns of the CDM Executive Board can be addressed. Even then, the proponents of a CCS project will have to be able to demonstrate that the technology and know-how to be transferred are sound and environmentally safe, and it will be up to the host country to decide whether a project contributes to sustainable development. Some of the largest developing economies have only relatively small storage capacity (in disused oil and gas fields) so wider use of CCS will depend on finding suitable deep saline aquifers. International organisations are helping to advance the understanding of CCS in various ways.

Deliberate programmes of public information by governments and industry will be needed to ensure that the public accepts this approach but it seems likely that most public interest in CCS will be in/around places where pipelines are installed or close to storage locations onshore.

Recommendations about policy options and other measures that could contribute to enhancing deployment and transfer of CCS technologies include:

1) Encourage novel ideas to reduce cost of CO_2 capture, recognising that existing technology presents stiff competition since it is also open to improvement.
2) Develop international standards for design and management of CCS facilities.
3) Support geological investigations in likely host countries to delineate, especially, potential for storage in deep saline aquifers.
4) Map the position of future sources (of all types) and potential storage sites to investigate feasibility.
5) Encourage the CDM Executive Board to support the use of CCS in developing countries.
6) Investigate potential for other funding bodies, such as GEF, World Bank, and Asian Development Bank, to support CCS projects.
7) Extend European Emissions Trading Scheme (ETS) in perpetuity. Substantially lower the cap in phase 3 (post-2012).
8) Encourage other countries to establish their own emission trading schemes and link them to ETS.
9) Encourage commercial sources of finance to take part in CCS activities e.g. European Investment Bank and others.
10) Assemble data to substantiate the claims of low leakage from storage facilities by further, monitored large-scale injection projects – ideally several in each region and with a variety of geological formations.
11) Promulgate understanding of the results of as many risk assessments as possible, to build confidence.
12) Encourage national development of suitable regulatory frameworks for CCS, taking account of experience elsewhere.
13) Improve public understanding of CCS as this could be a critical factor in determining the success of plans for large-scale deployment. Recognise that the timing of any public information campaign has to be coordinated with the need for awareness and a recognised wish by the public for information, otherwise it could be wasted or even counter-productive. Carry-out regular surveys of public attitudes in any country that is likely to want to use CCS, in order to calibrate changes in attitude.

14) Adopt policies for reducing greenhouse gas emissions which lead to stabilisation of the atmospheric concentration of CO_2 before the end of the 21st century.

15) Assess the level of understanding of the SBSTA about CCS before it is formally discussed and develop suitable, detailed briefings for that Body.

16) Encourage GEF to accept CCS as possible low-emitting technology suitable for future action.

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Sustainable Development and

CO_2 Capture and Storage

1. Introduction

CO_2 capture and storage (CCS) has attracted considerable interest in recent years because of two broad developments - the growing recognition of the threat of climate change, and the resurgence in understanding of the importance of fossil fuels to the world's economies. Another reason for the rapid rise in interest is that much of the technology is already available from commercial vendors, even if it is being applied for other purposes. Nevertheless, CCS is not a "magic bullet" – it cannot solve the problem of climate change by itself. Nor is it without cost, as well as other impacts, so in order to understand the role that CCS could play, it is important to have sufficient understanding to put it into context with other options for mitigating climate change. This report contains information on the status of CCS technology and its economics as well as an overview of current laws and regulations. It also presents a review of current trends and patterns of CCS technologies and seeks to identify the future potential as well as reviewing initiatives on CCS at global, regional and national levels, focussing on the more developed countries where most of the action is taking place at present.

The analysis of this information is used to identify the potential for advancing the deployment of CCS technology, including the development of the technology itself, the potential for global cooperation with an emphasis on the perspectives of developing countries, as well as challenges facing developers of the technology and potential hosts. Recommendations are presented for action, policy options are identified as well as other measures that could contribute to enhancing deployment and transfer of CCS technologies. The focus is on policy information relevant to promoting CCS technology, cooperation, diffusion and transfer.

This report has been commissioned by UN DESA as a background paper for an Expert Group which will consider the challenges associated with advancing the deployment and transfer of CCS technologies and the potential options and measures which could be used to overcome these barriers.

The following convention is used in this paper: million is represented by the letter M. All costs are reported in US $ or € using current exchange rates.

2. Technological Aspects of CCS

2.1. Overview

A brief overview of CCS technology is presented first. This draws on the major assessment of CCS technology which was published by IPCC as a Special Report (IPCC, 2005) supplemented by information on more recent developments.

2.2. Sources of CO_2

A key factor which determines the ease (and hence cost) of separating CO_2 from a gas stream is the concentration of CO_2. Higher concentrations of CO_2 make it easier to separate. Another factor important in determining process economics is the size of the plant - it is much cheaper (per tonne of CO_2) to separate CO_2 in large amounts than in small amounts. For this reason capturing CO_2 from small stationary appliances would be impracticable. Half of all fossil fuels are used in small burners (such as gas heaters) or in combustion engines in vehicles. The other half is used in large, industrial plant which is the most likely application of CO_2 capture. As Table 2.1 shows, about 75% of CO_2 from large sources comes from power generation. The flue gas streams from power stations contain relatively low concentrations (less than 15%) of CO_2. In contrast, several industrial processes produce higher concentrations of CO_2 including blast furnaces, cement kilns and, especially, ammonia and hydrogen production plants where the concentration of CO_2 can be as high as 100%.

Table 2.1 Global profile of large stationary sources of CO_2 (IPCC, 2005)

Source	CO_2 concentration (vol)	Number of sources*	CO_2 Emissions (Mt in 2003)
Power stations – coal/oil	8% - 15%	2540	8638
Power stations – gas	7% -10%	743	752
Power stations – gas/oil turbine	3% - 4%	1578	1085
Oil refineries+	3% - 13%	638	798
Blast furnaces	20% - 27%	180	630
Cement kilns	14% - 33%	1175	932
Ammonia production	100%	194	113
Ethylene production	12%	240	258
Natural gas processing	2% - 65%	†	50
Hydrogen production	<100%	†	†

Key:
* sources emitting more than 100,000 t of CO_2/year
+ including petrochemicals
† not given in reference

Many of the large sources of CO_2 are in developed countries and the distance to possible storage locations is, in many cases, less than 300km. Although sources of CO_2 (such as power stations) are certain to change in future, it is likely that, in the developed countries, they will be built on sites already used for such purposes so the correspondence with likely storage sites can be made with confidence now. However, in developing countries the situation is not so clear. For example, in China the amount of coal-fired generating capacity is increasing by about 12% every year, so it is likely that significant amounts of CO_2 might need to be captured at sites which currently do not produce CO_2. This means that, in rapidly expanding developing countries such as China and India, the location of current sources of CO_2 only provides a rough indication of where CO_2 might be captured in future.

2.3. Capture of CO_2

Two types of capture process have been in use (for other purposes) for many years and so are likely to form the basis for initial applications of CO_2 capture in power stations and elsewhere. These are post-combustion capture and pre-combustion capture. In post-combustion capture, CO_2 is separated from the other gases in the flue gas stream, which are mainly nitrogen. In pre-combustion capture, the fuel is converted into a synthesis gas with a high proportion of CO_2, making the separation easier.

Four general types of separation process are commonly discussed for use in capturing CO_2: absorption, using solvents; adsorption, using solid adsorbents; membranes; cryogenics, using low temperatures. Solvents can be used to capture CO_2 in a continuous process involving recirculation of the solvent between the absorber (where the CO_2 is captured from the process stream) and a regenerator, where a concentrated stream of CO_2 is released. Some processes use chemical solvents for this purpose and others use physical solvents – each has advantages for particular applications. Both can be configured to achieve high degrees of recovery and high product purity.

Chemical solvents are best suited for removing CO_2 at lower partial pressures where other separation processes are less effective (IPCC, 2005) - this is the preferred approach for post-combustion capture. In pre-combustion capture, the gas stream has a higher concentration of CO_2 as well as higher system pressure so physical solvents are competitive with chemical solvents and may even be superior, depending on conditions.

Pre-combustion capture involves a small modification to the design of the Integrated Gasification Combined Cycle power plant (IGCC), something which is now moving from demonstration to commercial deployment. As a result the plant will make a mixture of H_2 and CO_2, from which the CO_2 can be separated for storage. A similar approach could also be used in gas-fuelled plant. This is analogous to what is already done where hydrogen is manufactured although there the CO_2 is generally vented to atmosphere. A similar CO_2 separation process is used today in the large-scale production of synthetic natural gas from coal.

The preferred option for use in the current designs of power stations would be post-combustion capture using chemical solvent scrubbing. This has been used in various plants, some of which are still operating, to produce CO_2 as a product for the food industry and for use in enhanced oil recovery. None of these systems has handled as much CO_2 as would be needed for mitigation of climate change. Nevertheless there is confidence in the equipment supply industry that the necessary size of plant could be produced when there is commercial demand.

2.3.1. Other means of capturing CO_2

A third approach, now under development, is based on use of pure oxygen to burn the fuel instead of air, thereby avoiding the need subsequently to separate CO_2 from nitrogen. This is referred to as oxyfuel combustion – it has not been demonstrated at full scale in power generation but the concept is similar to one used in glass making.

Supplying the burners in a boiler with oxygen instead of air would result in very high temperatures, something which the boiler material could not withstand. To avoid this, some of the flue gas stream is recirculated to the boiler, moderating the temperatures to more conventional levels. The flue gas is a mixture of CO_2 and steam, with small amounts of other impurities such as oxides of sulphur. The steam can be condensed which would also remove some of the sulphur oxides. So with relatively little clean-up, a concentrated stream of CO_2 would be available for transportation for storage. The most likely application of this technique is with coal.

No other approach is at the stage where it could be considered for use in commercial plant without considerably more development and proving. Nevertheless there are some interesting ideas which may provide opportunities for improving the capture of CO_2 in future. One is an alternative to the conventional way of supplying oxygen (which uses cryogenics to separate it from air and is quite energy intensive). In this the fuel is reacted with a metal oxide, at high temperature. The chemical reaction releases heat and the fuel is converted into CO_2 and steam (and other impurities). At the same time, the metal oxide is converted into metal which is then removed from the reaction vessel. The metal is re-oxidised in a separate chamber before being returned to the combustion process again. Such a process, called chemical looping, potentially offers attractions compared with the established separation technologies but it has only been demonstrated at laboratory scale.

2.3.2. Fitting capture to existing plants

A topic of much current interest is the possibility of fitting CO_2 capture to existing power stations and other sources. The most likely approach would be to use post-combustion capture. However, simple *retrofitting* to existing power stations would be handicapped by the large energy consumption of the solvent scrubbing systems. The result would be a substantial reduction in the efficiency of plants which, because of their age, already have less than state-of-the-art efficiency. This would make them expensive to operate and thus unattractive for their owners to use. As a consequence, the emissions of any such retrofitted plant would be reduced, not by capturing the CO_2 but because they would be offline most of the time. In addition, the remaining life of an older station may not be sufficient to amortise fully the cost of the new equipment. Thus retrofitting existing power stations, unless they are recent, state-of-the-art units, would be unlikely to be commercially competitive.

Another approach, referred to in some countries as *repowering*, involves replacing major items of the existing power station as well as fitting capture. For instance this might involve fitting an ultra-supercritical boiler and steam turbine or even a gasifier and combined cycle turbines. In these circumstances, the life of the plant would be extended and the efficiency improved, so the addition of capture might become almost as attractive as fitting it in a new plant.

The term “capture-ready” is widely used to suggest building power stations in such a way as to make it easier to fit CO_2 capture at a later date. However, there is no precise definition of what this term would involve. Because of potential misunderstanding, we will try to avoid use of the term *capture-ready* in this report.

2.4. Compression and transport of CO_2

Once the CO_2 has been captured, it must be compressed for transport. This reduces the volume considerably which is beneficial for the size (and cost) of both the transport and the storage facilities. Typically CO_2 would be compressed to a pressure in excess of 7.4MPa; at these pressures CO_2 is said to be in its "dense phase". As a result its density is more than 700 kg/m^3 (i.e. close to that of liquid water). Industrial experience with gas compression is available to design and manufacture compressors for CO_2. The largest system currently in use is at the Dakota Gasification plant (USA) where 2 internally-geared centrifugal compressors supply CO_2 to the pipeline to the Weyburn oil field. A third compressor was ordered in 2006 to expand the supply. In other oil fields, reciprocating compressors are used for similar duties.

For full-scale power plants, pipelines are the preferred technology for moving CO_2 over distances of several hundred kilometres. Established long distance CO_2 pipelines in North America have capacity for 50 Mt CO_2/y; the oldest of these was built in 1984; there is a total 2600km of such pipelines in operation (Gale and Davison, 2003). Thus there is a significant body of experience with onshore CO_2 pipelines. Dry CO_2 does not corrode the carbon-manganese steels typically used for pipelines (IPCC, 2005) and moisture levels up to 60% relative humidity can be tolerated, even in the presence of N_2, NO_x and SO_x. However, the presence of free water leads to rapid corrosion, in which case stainless steel pipe would be needed, which is much more expensive.

In designing a pipeline, attention has to be paid to the possible consequences of leakage; the effects of leakage can be mitigated by choosing an appropriate distance between block valves to limit the amount released, by suitably locating the pipeline away from habitation, and by taking account of the fact that CO_2 is denser than air and so will sink into hollows. Accidents on the existing CO_2 pipelines have been found to occur with similar frequency to other long-distance pipelines. Preventative measures, such as increasing surface cover from 1m to 2m, reduced the frequency of damage to natural gas pipelines by a factor of 10 in rural areas and 3.5 in suburban areas (Gujit, 2004) and would also be relevant to the design of CO_2 pipelines.

The initial CO_2 capture projects in a particular area would likely transport CO_2 from one power plant to one storage location. However, such an approach would suffer relatively high specific costs (i.e. \$/tonne) for transport. If several plants were to be equipped with capture, the transport costs (per tonne) could be reduced by building larger diameter pipelines. However, establishing such a network would require large initial investment, which may not be remunerated by the early uses.

2.5. Storage of CO_2

Many ideas have been proposed for storing CO_2 but most of them suffer from the following problem: if storage of CO_2 is to have a significant impact on global emissions (currently about 26 $GtCO_2$/year), there will need to be sufficient capacity to accept a reasonable fraction of these emissions for the next 50 or 100 years. This suggests that a global capacity of order 300 Gt CO_2 would be needed. The only storage options which offer such capacity are natural reservoirs – especially geological formations or the deep ocean. As dumping waste into the deep ocean is prohibited by the London Convention, this suggests that geological formations are the places where it is most likely that CO_2 will be stored.

The requirements for geological formations to store CO_2 are broadly as follows: the formation must be deep enough for CO_2 to be in the *dense phase* (a depth of at least 800m); there must be a cap rock impervious to CO_2 to hold it in place for thousands of years, at least; the porosity of the formation must be great enough to hold the required quantity of CO_2; the permeability of the formation must be sufficiently high that the CO_2 can move through it with ease. There are various mechanisms by which CO_2 will be held underground. Numerical models of CO_2 stored underground show that storage should become more secure with the passing of time, becoming highly secure within 100 to 1000 years of injection depending on the type of reservoir (IPCC, 2005).

2.5.1. Storage options

A geological formation that has already been exploited as a source of hydrocarbons would be potentially attractive as a site for storage of CO_2, not least because of its demonstrated ability to retain these fluids, plus the fact that it will have been investigated and surveyed. Providing that subsequent penetrations of the cap rock have not compromised its ability to retain CO_2, such formations should make good storage reservoirs.

Because of the commercial value of oil production, CO_2 is unlikely to be injected into oil fields until as much oil has been extracted as possible - this may be as much as 60% of the original oil in place although the worldwide average is only 35% (IEA, 2005). Thus CO_2 storage will most likely take place in partially-depleted fields. Injection into a partially-depleted oil field for storage has not yet been attempted on a commercial scale.

Conventional gas production extracts a larger fraction of the original amount than is the case with oil production - up to 95% of natural gas can be recovered by conventional production, so injection of CO_2 into gas fields for storage is likely to take place into essentially exhausted gas fields (exceptions to this are discussed below). The K12-B field (offshore the Netherlands) was the first to inject CO_2 into a depleted part of a gas field.

The potential global capacity of known oil and gas formations to store CO_2 has been estimated to be 675-900 Gt CO_2 (IPCC, 2005), most of which would be in gas fields.

Geological formations filled with salty water (saline aquifers) are thought to occur much more widely than oil or gas fields but they have no commercial value and so have not been explored to anything like the same extent. Nevertheless the first commercial-scale storage of CO_2 (the Sleipner project, offshore Norway) made use of a deep saline aquifer, about 1000 m below sea-level. This started operation in 1996 in conjunction with production of natural gas from the Sleipner Vest field. The Snøvhit project, which will be Norway's second CO_2 storage project, also uses a deep saline aquifer for storage; this will start operation in 2007. The Gorgon project (offshore Australia) will inject CO_2 into a deep saline aquifer sometime after 2009. Deep saline aquifers are believed to be widely distributed in sedimentary basins around the world. The potential global capacity is much larger than for oil and gas fields – probably in excess of 1000 Gt CO_2 (IPCC, 2005).

Coal is capable of physically adsorbing a variety of gases, especially in its micro-pores. Gaseous CO_2 injected into the coal would flow through natural fractures before being adsorbed into the bulk of the coal. For storage purposes, the coal seams in question must be protected from any future mining, otherwise the stored CO_2 might be released, thereby negating the purpose of the original injection. The mechanisms of trapping dense phase CO_2 in coal are not well understood (IPCC, 2005). The CO_2 can affect the structure of the coal as well as cause the coal to swell. Global storage capacity has been estimated theoretically as 60 to 200 Gt CO_2 but, taking account of permeability, the cost-effective capacity for storage may be only around 15 Gt CO_2 (Freund, 2001).

Basalt formations offer the possibility for reaction with the injected CO_2, producing a solid mineral which would guarantee secure storage. This concept is still in the research phase, which is addressing means of improving CO_2 flow in the relatively impermeable basalt and enhancing the mineralization reactions.

2.5.2. Use of CO_2 to enhance the recovery of hydrocarbons

Injecting CO_2 for long-term storage, whilst it has environmental benefits, misses any opportunity to make use of the CO_2 as has been done by the oil industry for several decades to enhance production of oil. Enhanced oil recovery (EOR) exploits the dissolution of CO_2 in the oil, under appropriate circumstances, making it easier to move the oil to the production well. Some of the injected CO_2 will be produced with the oil – it is normal practice to separate this and re-inject it. The CO_2 remaining in the reservoir at the end of injection can be regarded as being stored, providing no further use is made of that field. The recent US Roadmap (US DOE, 2007) implies that 80% of the purchased CO_2 would remain stored in the formation. This also requires that the formation remains sealed, preventing escape of CO_2 at a later date. US experience with onshore EOR projects (IPCC, 2005) suggests that, on average, 0.3 t CO_2 is purchased for each additional barrel of oil produced.

The Weyburn oil field in Canada is the first CO_2-EOR project which also has monitoring of the CO_2 stored in the reservoir; this has been operating since 2000. No offshore EOR has been undertaken anywhere in the world although projects have recently been proposed in UK and Norway.

In the case of gas fields, there is less need to enhance the ultimate recovery because a large part of the gas can be produced by conventional extraction methods. Nevertheless, it might be feasible to enhance gas recovery in partially depleted fields (Oldenburg, et al., 2004); alternatively CO_2 (or other suitable gases) might be used to improve the rate of recovery of gas in the early years of production by maintaining reservoir pressure. At some point the CO_2 may mix with the natural gas – such contamination adds cost (for separation) which has to be traded off against the benefit of maintaining early production. The first practical example of injection of CO_2 into a new gas field is taking place at the In Salah field complex in Algeria where CO_2 extracted from the produced gas is being reinjected. Reinjection into a depleted gas field is being tested at the K12-B field offshore the Netherlands.

Injection of CO_2 into coal-beds containing methane (adsorbed into the coal) has been shown to preferentially displace coal-bed methane (CBM) from the coal as the CO_2 is adsorbed. The most successful examples of this have been in US coals with high permeability, which allows the CO_2 to move easily through the coal-bed. The CBM can be sold to help offset the cost of injection. The first project where CO_2 was injected into coal was the Allison project in the USA where the aim was to enhance CBM production. Subsequently CO_2-enhanced coal bed methane (CO_2-ECBM) projects to investigate enhanced production and CO_2 storage have been conducted in the Fenn Big valley in Canada, at the Recopol project in Poland, in Australia and in the Qinshui basin in China. In some cases, nitrogen has also been injected as this can assist methane production.

2.5.3. Analogues of geological storage of CO_2

Engineered stores are used to hold natural gas in many countries in order to allow excess gas production during summer to help meet peak demand in winter, and to ensure supplies are available in case of short-term disruptions. This is done in 634 individual facilities in 25 countries (IEA GHG, 2006). The largest amount of natural gas storage is in USA and Russia. The total capacity is about 340 billion m^3 of gas, which would be equivalent to the space required to hold 270 Mt of CO_2 (if it was in the dense phase), so this is a relevant scale of experience.

Indeed natural gas storage may be a competitor to CO_2 storage for use of some geological formations. The main formations used to hold natural gas are depleted gas or oil fields and, to a lesser extent, aquifers. Another close analogue of CO_2 storage is the injection of acid gases (i.e. CO_2 and H_2S) into geological formations in Western Canada and, to a lesser extent, the USA. Up to the end of 2003, 2.5 million tonnes of CO_2 had been injected in this way in 50 projects in Canada, mainly into deep saline aquifers but also into depleted oil and gas fields.

There are also natural CO_2 fields, which can be good places to learn about the storage of CO_2. For example, where there are slight leaks, these provide the opportunity to develop techniques for monitoring storage. Also, the natural fields provide information on the long-term performance of the cap rock, which is the best test-bed for the types of geological seal that will be exploited in the storage of CO_2.

Properly designed CO_2 stores should be able to emulate nature and retain CO_2 for a long time. Major failure of injection wells in engineered stores has occurred with an average frequency of only once in 20,000 to 50,000 years of operation (IPCC, 2005).

2.5.4. Monitoring and verifying storage of CO_2

Any rapid leakage from a store would need to be detected in case it presented a threat to human life or the local environment – appropriate detectors are built into any such injection project. However, slow leakage could, over the long term, negate much of the climate benefit of injecting CO_2 into geological formations. Such leakage might be at a lower level than the natural background flux of CO_2 at the surface, so that measurements must be taken sub-surface and/or using isotopic analysis or by use of tracers. No evidence of such CO_2 leakage has been reported to date but relatively little work has been put into detecting it.

Monitoring of CCS projects is needed to verify that CO_2 is not leaking from the store to any significant extent, and to satisfy the authorities reporting national emissions to the United Nations Framework Convention on Climate Change (UNFCCC), as well as to provide a basis for funding the scheme.

Initially the amount of CO_2 injected may be reconciled with the amount detected in structural traps as measured, for example, by a seismic survey. However, in the longer term, as other trapping mechanisms become more important, it will be more difficult to detect the CO_2 in the formation so ongoing verification of the amount of stored CO_2 will tend to rely on various types of geological model, accompanied by near-surface measurements to determine whether any leakage is taking place.

3. Performance and emissions of CCS plant

Having briefly introduced the technology of CCS, we now examine some of the effects that its use will have on the plant to which it is fitted. Because of the dominance of power plant emissions in the overall statistics (Table 2.1), the examples given here are based on that type of source but similar data can be produced for hydrogen production, oil refineries and other large stationary sources.

3.1. Performance of CCS plant

The amount of fuel used by a power station fitted with CCS is greater compared than that used by a plant of similar output without CCS because of the energy used by the capture equipment and to drive the CO_2 compressor. Representative values are given in Table 3.1 for power stations of 400-800 MW rating. Three types of power station are considered – pulverized coal (PF) with post-combustion capture, integrated gasification combined cycle (IGCC) with pre-combustion capture and natural gas combined cycle (NGCC) with post-combustion capture. It is assumed for purposes of this comparison that the electrical output of the plant is the same with and without CCS.

Table 3.1 Extra energy used by power plants with CCS (IPCC, 2005).

	PF	IGCC	NGCC
Plant efficiency with capture (LHV)	30-35%	31-40%	47-50%
Increase in fuel requirement	24-40%	41-61%	31-50%

This demonstrates one of the key aspects of the use of CCS, namely that it would result in increased consumption of fossil fuels. At the same time, the emissions of greenhouse gases would be substantially reduced as will be shown below.

3.2. Emissions from CCS plant

Emissions from a power station will be reduced by use of CCS by 80% to 90% (see Table 3.2). The precise extent of the emissions reduction will depend on the configuration of the plant. Representative values are shown for the same types of power station as in Table 3.1. For illustrative purposes it is assumed that all compression of CO_2 takes place at the power station site and that there are no emissions at the injection point (although this would not be the case for an EOR project).

Table 3.2 Representative values of CO_2 emissions from power plant with and without CCS (IPCC, 2005)

	PF	IGCC	NGCC
Emission without CCS (kg CO_2/MWh)	762	773	367
Emission with CCS (kg CO_2/MWh)	c.100	c.110	c.60
Emissions avoided (kg CO_2/MWh)	c.660	c.660	c.310
Fraction of CO_2 emissions avoided	87%	86%	84%

3.3. Leakage of CO_2 from storage

The basic assumption underpinning the concept of CCS is that CO_2 can be stored underground safely and securely for thousands of years, to beyond the time at which anthropogenic climate change would be a threat to human existence. The strength of this assumption is based on the observation that fluids such as oil and natural gas (even CO_2) have been held in natural geological formations for millions of years. Because of the novelty of the CO_2 storage concept, there is only a limited amount of information available from CO_2 injections carried out to date which would allow an assessment to be made of the likelihood of leakage. The assumption can be tested, to an extent, by examining the behaviour of natural CO_2 fields which in some ways are analogues of deliberate storage of CO_2. As mentioned before, there are also man-made analogues, such as the storage of natural gas, which also demonstrate what could be done with CO_2.

4. Economics of CCS

Energy supply systems make use of finite resources. Sustainable systems might be thought of as ones which make best use of resources, i.e. achieving the greatest effect with least damage. For example, sustainable systems might be chosen so as to have least impact on the climate but also to make best use of other physical resources, such as metal or concrete, as well as other factors such as labour. Such systems do not exist in isolation but supply services to others - so issues of cost and reliability of service will also be relevant in determining their competitiveness with other means of serving the same need. In order to form a judgement about any particular method of energy supply method, it is necessary to appraise many aspects. Perhaps the only universal system for such assessment is economics.

Many studies of the economics of CO_2 capture and storage have been published; several of them were summarised in the IPCC Special Report (2005). Provided the circumstances are similar, and fuel prices, usage patterns and discount rates the same, it is reasonable to compare different studies to investigate the effects of particular changes in configuration. However, there are few established conventions for this (2 examples are the EPRI Technology Assessment Guide, and the IEA Greenhouse Gas Programme's basic assumptions, which were based on EPRI's method). Unless a common framework is used, it can be misleading to compare the results of different studies on the economics of these plants.

By convention, compression is considered together with the capture stage because the compressor is located on the power station site; the electricity consumed by the compressor is included with other ancillary uses on the site. Pipeline and storage costs are typically assessed separately and added to the cost of capture and compression to produce whole system costs. The cost of the owning and operating power stations is expressed in terms of levelized cost.

4.1. Standard assessments

A number of assumptions have to be made in order to standardise evaluations. These help to avoid a number of sources of uncertainty, allowing discussion to be focussed on key differences between technology options. One of these concerns the output of the plant. Because of the energy requirements of the capture process, power stations are assessed at a particular output (e.g. 500MWe), with and without capture. Unless this is done, the plant with capture (which would have lower output) would not carry the full cost of generating the required amount of electricity. Also there are economies of scale in constructing and operating plant which mean it is less expensive (per kWh) to build a larger station to achieve the required output than expect other (smaller) stations to make up the difference. Such extra costs and emissions can be allowed for easily by assuming that the stations with and without capture have the same output.

The disadvantage of this approach is that it may involve different sizes of turbines or different configurations than might be considered practicable. However, especially if different types of technology are to be compared (e.g. IGCC compared PF), a standardised basis for assessment is essential.

4.1.1. Economics of CO_2 Capture

A selection of results reported in IPCC (2005) is reproduced in Table 4.1. These were derived by the authors of that report from a number of studies published between 2003 and 2005 with costs adjusted to 2002 US $ values. Fuel prices used in these studies were between US $1.0 - 1.5/GJ for coal and US$ 2.8 - 4.4/GJ for natural gas. These may not be representative of current values - changes in these figures will have a significant effect on the calculated results. Many other inputs have also changed in price since then, so these cost figures should be treated with some caution.

The capital costs of the plants with and without CO_2 capture and compression are represented in terms of specific costs – namely the capital cost divided by the nominal output of the plant. The load factors of the plants are between 65 and 85% for coal-fired stations and 50 to 95% for gas-fired stations.

Table 4.1 Representative values of cost of capture for new power plant with and without CCS (IPCC, 2005)

	PF	IGCC	NGCC
Capital cost without capture (US $/kW)	1286	1326	568
Capital cost with capture (US $/kW)	2096	1825	909

4.1.2. Economics of transport of CO_2

The cost of a pipeline includes construction, operation and maintenance. It is strongly influenced by the capacity of the line and the terrain to be crossed; offshore pipelines tend to be more expensive than onshore pipelines. Intermediate compressor stations may be required to compensate for pressure loss on longer pipelines. To transport 6 Mt/y CO_2 (the quantity of CO_2 produced by capture in a 800MW IGCC) over a typical distance of 250km in a pipeline of about 300 mm diameter would cost about $2-3/t onshore and $3-4/t offshore (IPCC, 2005). The cost of transport rises proportionally with distance (not including the cost of any booster compressors required). Smaller quantities would cost considerably more; for example transport of 3 Mt/y would cost about $3-5/t over a distance of 250km onshore in a pipeline of about 200 mm diameter.

4.1.3. Economics of storage of CO_2

The main expenditure involved in geological storage is for exploration and for drilling wells – the latter will be influenced by the type of rock, number of wells, depth and injection rate, amongst other things. The type of reservoir (oil or gas fields or saline aquifers) is less important than the permeability, thickness and depth of the formation (IPCC, 2005). The CO_2 will be delivered to the storage site under pressure but may need to be further pressurised (depending on the depth of the well) which would be an additional expense.

Although it is difficult to generalise about storage costs, it is expected that, for commercial-scale storage, costs per tonne of CO_2-stored will be considerably less than for capturing the same amount of CO_2, so uncertainty in the cost of storage has limited effect on accuracy of the overall cost of capture and storage. In any particular region of the world, there will be a range of opportunities with different costs. In a review of published estimates of storage costs (IPCC, 2005), the middle of the ranges quoted in various studies was \$0.5-8/t CO_2-stored.

Enhanced oil recovery involves greater capital and operating costs than injection purely for storage. In addition to the injection wells, there may need to be extra production wells (in addition to those already in use in the field) as well as separators and compressors to re-inject CO_2 produced with the oil. The cost of these items should be offset by the income generated by the extra oil produced. No studies have been published of the economics of EOR at current oil prices but some indication of the benefit of onshore EOR can be gained from considering the price paid by EOR operators for CO_2 – these range from \$12/t at \$18/bbl oil, to \$33/t at \$50/bbl (IPCC, 2005). This gives an indication of the income which might be available to help offset the cost of capturing and transporting CO_2 to the site.

The costs of storage will also be affected by the monitoring requirements. Monitoring can represent a large proportion of the overall cost for a small project but, for full scale projects (e.g. storing tens of millions of tonnes of CO_2 per year), the cost can be expected to be less than \$1/t CO_2-stored discounted over the operational lifetime (Benson et al., 2004). If any remedial action needs to be taken, this will be an additional cost; there may be other costs in the longer term connected with the ending of injection and the sealing of the injection wells but these have not yet been defined precisely.

4.1.4. Whole system economics and capacity

Overall costs of electricity produced by these plants are illustrated in Table 4.2 based on studies of the type described above, and allowing for cost of pipelines and storage. The discount rates used were typically between 9% and 12.5%. The effect of introducing CCS was to increase the cost of electricity generation by 40% to 90% although it should be noted that the cost of electricity supplied to the customer will not rise as much (in % terms) because other costs, such as distribution, would not increase to the same extent.

Table 4.2 Representative values of cost of electricity generated by new power plant with and without CCS (IPCC, 2005)

	PF	IGCC	NGCC
Cost of electricity without CCS (US$/MWh)	43-52	41-61	31-50
Cost of electricity with CCS (US$/MWh)	63-99	55-91	43-77
% increase	43-91	21-78	37-85
Cost of CO_2 emissions avoided (US$/t CO_2)	30-71	14-53	38-91

From these figures, values of the cost per tonne of CO_2-avoided can easily be calculated relative to a stated base case. Thus the cost of CO_2-avoided by an IGCC with capture can be calculated by comparison with an IGCC without capture. However, it should be noted that the cost of CO_2-avoided by such an IGCC with capture would be different if compared with a PF power station using the same coal. This difference is relevant since, at present, PF is the least-cost way of using coal, and so is the type of power station that would probably be built in the absence of other constraints. Comparing the IGCC with capture against anything other than the least-cost option runs the risk of biasing the results (expressed as cost of CO_2-avoided) in favour of the IGCC.

It is noted that expressing costs in terms of tonnes of CO_2-avoided is also the method of presentation used by energy modellers when considering mitigation options for, say, a national electricity system. It is also the language used to indicate the market value of avoiding CO_2 emissions. In such cases, the base case for comparison will typically be the marginal plant on the grid. This variation in basis for comparison could be confusing. Just because the numbers look to be equivalent, it does not mean that the figures should be compared without checking the basis is the same.

4.1.5. Economic potential

In order to understand the economic potential of CCS it is necessary to simulate the use of this technology in global and regional energy systems in competition with other supply and demand options. This can be done by use of integrated assessment models (based on computable general equilibrium economic models – so called top-down models) or by use of engineering optimisation models (so-called bottom-up models). IPCC (2005) surveyed a number of studies done using these models, especially for CCS used in electricity generation. A range of scenarios of future energy use were considered based on the 6 SRES families produced by IPCC (2000). Such scenarios allow us to test our expectations of the future against a range of ideas about what might happen.

Table 4.3 CO_2 storage (Gt CO_2) required between 2000 and 2100 depending whether stabilization is to be at 450 or 550 ppmv averaged across the 6 scenarios (IPCC, 2005).

	Stabilization at:	
Storage in:	550 ppmv	450 ppmv
OECD (as at 1990)	242	551
Former Soviet Union	87	319
Asia	296	638
Rest of the World	273	652
World total	898	2162

Due to the large number of variables possible in such analysis, only a small selection of the results will be presented here. Table 4.3 shows the total amount of CO_2 storage which would be used by the models in the period 2000 to 2100 for the 6 representative scenarios with the aim of achieving stabilisation of atmospheric concentrations at either 550 ppmv or 450 ppmv[1]. The requirements for storage vary amongst the different regions of the world.

Another way of looking at the results is to see how these depend on the scenario of economic activity; we consider 3 of the scenario families A1B, A2 and B2 (IPCC, 2000). Table 4.4 shows that the demand for CO_2 storage capacity is consistent with current knowledge of the potentially available global capacity (see chapter 2). However, because the storage capacities in each region were not introduced into the models, the fact that the models show that a certain amount of storage could be used in a particular region does not mean this is practicable. Hence these capacity figures should be treated with some caution until further information is available on the distribution of storage capacity.

Table 4.4 CO_2 storage (Gt CO_2) required between 2000 and 2100 for different scenarios (IPCC, 2005) assuming stabilization at 550 ppmv

	Marker scenario		
Storage in:	A1B	A2	B2
OECD (as at 1990)	202	174	115
Former Soviet Union	99	55	79
Asia	226	153	67
Rest of the World	214	124	63
World total	740	505	324

If other mitigation options also use CCS, such as the manufacture of hydrogen from fossil fuels as a vehicle fuel or the use of CCS with biomass, greater capacity would be required but this should still be within current expectations of storage capacity availability.

Another important aspect of these models is that they provide an indication of the contribution that CCS could make to achieve the chosen stabilisation target. For the models reviewed in IPCC (2005), the average share of emission reductions from use of CCS was 15% for scenarios aiming at

[1] Because the atmosphere currently contains 380 ppmv of CO_2 and this level increased by around 20 ppmv in the past 10 years, it is hard to see how the 450 ppmv target could be achieved without drastic action to cut emissions immediately.

stabilisation at 750 ppmv rising to 54% in the case of stabilisation of 450 ppmv. Because of the way the models work, this indicates that there would be substantial cost savings from use of CCS compared with meeting the same targets without use of CCS. Although the IPCC (2005) data did not provide data on the extent of these savings, other references (Edmonds et al., 2000, McFarland et al., 2004) do indicate substantial savings.

4.1.6. The first plants of this type

All of the discussion above has concerned costs estimated for established power generation technology which are installed in quantity. As yet, no full size power plant has been built with CCS and the first ones will likely be more expensive than indicated in Table 4.2. There are various reasons for this including the lack of familiarity of the constructors with the system and the absence of economies of scale in manufacture. As experience is gained with building such plant, the costs will reduce. Such trends are typically represented by "experience-curves" which show how much reduction in capital cost can be expected as experience is accumulated with the new type of plant. Such curves have been produced for several technologies that are relevant to CCS, for example flue gas desulphurisation (FGD) in power stations. Analysis of various process technologies has shown that capital costs typically have been reduced by 10% to 15% for each doubling of installed capacity with associated reductions in operating and maintenance costs (Rubin, et al., 2004). The same is expected to happen with CCS.

5. Other Aspects

Application of CCS will depend not only on technology and economics but also on the methods of financing the projects and on the form of regulation. The regulation of CCS will also determine the requirements for monitoring and verification of the projects. Methods of financing and regulation are under development at present so an overview of the current status will be provided below.

5.1. Legal and Regulatory aspects

For onshore operations, capture and pipelining of CO_2 can probably be dealt with under existing national laws for such plant – each country is likely to examine its laws to clarify the specific requirements (e.g. Germany and the UK are doing this at the moment). Offshore, and in particular outside territorial waters, the use of CO_2 storage will be controlled by the London Convention, and its later Protocol, which regulate the disposal of waste materials at sea. National and regional conventions built on the London Convention/Protocol, such as the OSPAR Convention for the North-East Atlantic, set the requirements in particular areas of the ocean. Recently, both the London Protocol and the OSPAR Convention have accepted changes to allow storage of CO_2, captured onshore, in sub-seabed geological formations (although OSPAR has yet to ratify these changes).

For example, Annex 1 to the London Protocol was amended in 2006 to the effect that a CO_2 stream from capture processes for sequestration may only be considered for dumping if:

- disposal is into a sub-seabed geological formation;
- it consists overwhelmingly of CO_2. It may contain incidental associated substances derived from the source material and the capture and sequestration processes used;
- no other wastes or other matter are added for the purpose of disposing of those wastes or other matter.

This amendment came into force in February 2007. Draft waste assessment guidelines were discussed at a meeting in May 2007. These will form the basis for permits which would be issued for injection of captured CO_2 into sub-seabed geological formations. Similar conditions for storage of CO_2 are likely to be adopted by OSPAR. Various conditions are imposed by these Conventions but these developments have clarified the legal position of offshore storage of CO_2, if done in the right way. Other rules may also affect CO_2 storage, such as the European Water Directive which protects water supplies. Recognising this, European Commission has indicated it will develop a regulatory and policy framework for CCS in the EU in order to ensure the environmentally sound, safe and reliable operation of CCS activities, and remove unwarranted barriers to CCS activities in current legislation.

The regulatory framework for CO_2 storage is likely to be based on an integrated risk assessment, with site selection procedures designed to minimise the risk of leakage, and monitoring/reporting regimes designed to verify storage, as well as remediation procedures to deal with any leakage that does occur.

It is unlikely that many CCS projects will be designed to be international in structure, at least in the early days, because of the legal restrictions on the international transport of a waste material. The Weyburn project may remain as the sole example of this for some time to come.

5.2. Risk Assessment

In order to gain regulatory approval for a CO_2 store, it is likely that the operators will have to conduct a risk assessment, to identify possible leakage paths, to estimate the likelihood of leakage and any potential consequences. They will consider 3 main types of effect: hazards to human health or safety; effects on groundwater and ecosystems; effects on climate.

A hazard to human health would arise from concentrations of CO_2 of more than 1% to 2% which might happen if the escaping gas was somehow confined in a restricted space. Such a threat, whilst improbable, might occur if someone drilled into the formation whilst the CO_2 still existed as a discrete phase. This could be avoided by ensuring appropriate licensing of the area of the storage site.

Groundwater might be affected if toxic metals were leached by acidic water containing dissolved CO_2; the worst outcome would be if this affected drinking water. Experience with injecting other fluids underground indicates such outcomes are rare. Nevertheless, if CO_2 contained impurities such as sulphur, the consequences would be more severe than with pure CO_2 which suggests that in most places storage will have to be restricted to relatively pure CO_2.

Without having precise figures on the likelihood of leakage, we cannot make an absolute statement about the effect this would have on the climate but we can ask whether there is a threshold below which there would essentially be no harmful effect on the climate? By use of climate models, it has been found that if 99% of the CO_2 can be stored for a period that exceeds the projected time span for the use of fossil fuels, this use of CCS should be able to contribute to stabilising the amount of CO_2 in the atmosphere (IPCC, 2005). Our understanding of geological storage gives confidence that this can be achieved.

5.3. Reporting of CCS projects

Countries listed in Annex 1 of the UN Framework Convention on Climate Change (UNFCCC) must report their greenhouse gas (GHG) emissions annually in National Inventory Reports (NIR). Such reports make use of the relevant IPCC Guidelines. The 2006 Norwegian National Inventory Report was the first to include emissions from a CO_2 storage facility, including a description of the method of measurement used. Also in 2006, the IPCC released a revised version of its *Guidelines for national emission inventories* (IPCC, 2006). This made specific provision for accounting for CCS projects although implementation of these Guidelines may take place at any time up to 2012.

The experience of successful storage projects is being drawn together in best practice manuals which will eventually form the basis for codes of practice, as have already been developed for underground natural gas storage facilities. It can be anticipated that a code of practice would cover issues such as selection of sites, testing of reservoirs and cap rocks, acceptable injection conditions (especially to avoid damage to the geological formations), monitoring during injection and afterwards, closure methods and remediation in case of leakage.

5.4. Liability for stored CO_2

The operator is responsible for the stored CO_2 and any associated liabilities throughout the injection phase. Since commercial organisations, such as the project operator, tend to have only a finite life, it will be necessary at the outset to ensure that suitable provision is made for handover of responsibility as/when necessary. Once injection has ended and the reservoir is in a stable state and there is agreement between the models of the reservoir and the observed systems, decisions can be taken about who should be responsible for it in future. The obvious body to take on long-term responsibility is the government but it will want to be sure that the operator does not shirk any of its duties because it knows that the government is standing behind it.

In Australia the federal and state governments drafted a regulatory framework to describe the circumstances under which government might accept stewardship of the stored CO_2. In particular it proposed that the government would not accept this responsibility until it was satisfied, in particular, that the risks of leakage and liability were acceptably low, and that ongoing costs associated with the site were acceptable and/or properly provided for, for example through a trust fund. This would be embodied in an agreement made with the operator at the start of the project.

5.5. Making judgements about the sustainability of CCS

One of the problems in examining the sustainability of an energy system is to take a comprehensive view of the environmental impact of the system. The accepted methodology for doing this is Life Cycle Analysis (LCA). Relatively few LCAs have been conducted of power generation with CCS. One of the first (Waku et al., 1995; Akai et al. 1997) examined energy and emissions for both LNG combined-cycle and coal IGCC systems incorporating CO_2 capture and storage. The total energy required for construction, operation, and maintenance of the system was included in this analysis. Another study (Spath et al., 1999) mentioned CCS in an LCA study of renewable energy systems but did not assess the CCS option, restricting analysis to conventional fossil-fuel fired systems. Several LCA of coal and gas fired power generation systems with CCS were examined in a study (Audus and Freund, 1997) carried out as part of a cost-benefit analysis of options for CCS which included modelling the climate benefits of reduced CO_2 emissions by use of externalities of climate damages avoided. Viebahn et al. (2007) reported LCA of CCS together with a comparison of the economics of CCS with renewable energy supplies for power generation in Germany.

Although this is a relatively small number of studies from which to draw conclusions, in general it seems that conclusions are not that different from conventional analysis based on private costs and power plant emissions; several of these LCAs demonstrated that ancillary effects, such as methane emissions from coal mining, would increase but the difference from conventional economic analysis is one of degree rather than radically altered conclusions.

Another important aspect of CCS will be its acceptability to the public at large. Limited effort has been given to finding out public attitudes about this anywhere but initial surveys indicate that geological storage may be acceptable to the public under certain circumstances (e.g. in Britain, such a study was reported by Gough et al., 2002). A recent comparative study (Reiner et al., 2006) of public attitudes in the USA, UK, Sweden and Japan towards key questions about energy and the environment, also examined attitudes towards CCS. The survey found little awareness of, or understanding about, CCS. Mixed views were expressed about the role of CCS in a portfolio of energy technologies or as part of a national climate change policy.

Another key aspect of sustainability in relation to use of CCS concerns the use of finite fossil fuel resources. As shown in section 3, use of CCS would increase the energy consumed by a power plant by 25 to 50% compared with production of the same amount of electricity without CCS. Clearly this is a disadvantage of the approach and a judgement has to be made about whether this is balanced by other aspects of its contribution to sustainable development. A corollary of this concerns the increased cost of electricity compared with current costs - all other things being equal, this increase would tend to reduce the demand for electricity which would constrain the increase in use of fossil fuels to some extent.

Nevertheless, in a period of rising energy prices and uncertainty about the reliability of supplies, countries with national hydrocarbon resources are inclined to make best use of them – so we see China developing coal-using technology for making transport fuels and the USA also developing this technology as well as exploiting unconventional sources of oil and biofuels; in Venezuela, the state is increasing its control of oil and gas production through nationalisation, whilst in Russia the state's influence on, especially, gas production has been increased via that country's major production company; similar changes are happening elsewhere too. Such developments encourage the use of national fuel resources, especially coal, with consequent increase in greenhouse gas emissions unless CCS technology is brought into use (MIT, 2007). However, only one of the above countries, Russia, has accepted limits on national emissions of greenhouse gases and, whilst many developed countries may think it a good idea to use CCS, there is little incentive for countries such as China and Venezuela to take such action.

In order to justify use of CCS in power generation it will be necessary for the host country to accept the need for deep reductions (>80%) in emissions from power generation, which would also tend to raise the marginal price of CO_2 emission allowances. Logically this is also a necessary condition to justify investment in most renewable energy technologies but, in practice, most Western countries do not seem to have let this inhibit them from subsidising such projects, possibly because there needs to be some pump-priming of a new industry to establish it in the market place. Other applications of CCS, such as with concentrated sources of CO_2 emissions, would be relatively inexpensive and so could be justified without the need to accept deep reductions in emissions – for example, in ammonia manufacture; the same could apply to emissions from coal-to-liquids plants. These can be recognised as potential early opportunities for application of CCS.

Another such early application might be use of CCS with biomass fuel, which would serve to draw-down CO_2 from the atmosphere. Although there are limitations on how much contribution this technique could make because of limitations on supplies of biomass in developed countries, this is a unique contribution that CCS could make to tackling climate change.

6. Status of CCS

Since the publication of the IPCC Special Report (2005) on CCS, activity has increased markedly. Several commercial projects have been announced, albeit with reservations about when the CCS component will be fully functioning, as well as some government initiatives to bring forward demonstrations. These are summarised below.

Full scale CCS plant will require substantial financial investment over a relatively short period of time - for example, in Europe a proposed fleet of 12 CCS-equipped coal- or gas-fired power plants (each of 300 MWe) would require at least €5000M of investment which, might have to be spent within the next 7 years. Such large spend is likely to require some form of support from government so the status and prospects for CCS are closely related to national plans. For this reason, the following review of CCS projects is presented by country for a selection of the major countries involved; national initiatives to encourage use of CCS are summarised in a similar way in the following chapter.

6.1. Investments in CCS

6.1.1. Germany

Out of 38GW of new power plant expected to be constructed by 2016, ? will use coal as fuel (RWE, 2007). One of the major companies, RWE, has announced plans to build one 450 MW IGCC power plant with CO_2 separation and storage, to come on-stream in 2014. The plant would cost about €1000M. CO_2 storage would be onshore, presumably in a saline aquifer but this has not yet been announced. In order to meet the 2014 timetable, the power plant design as well as investigation of the storage facility must proceed in parallel, so that design and permitting of both parts can be completed by 2010. However, investment in the plant will depend on a suitable financial climate being established. RWE has indicated that it is looking to government to provide the necessary long-term and stable investment conditions.

Swedish-based electricity company Vattenfall has started construction of a 30MW lignite power plant using oxyfuel combustion technology at Schwarze Pumpe near Cottbus in Germany. This is scheduled to be operating in 2008. It is seen as the pilot for a full-size lignite-fuelled power plant with CO_2 capture. Vattenfall is investing €50 million in building the plant. The captured CO_2 will be compressed for transport but the storage location has not yet been announced.

6.1.2. Netherlands

Under the government-supported ORC (Offshore Re-injection of CO_2) project, Gaz de France has been reinjecting CO_2 at its K12-B field offshore the Netherlands since 2004. This will eventually demonstrate full scale injection of CO_2 into a compartment of the depleted gas field. Initially, about 60 t/day of the CO_2 was re-injected into the field (well number 8) as a test of the concept. Subsequent to that, injection into a different compartment of the field has started with the aim of testing enhanced gas recovery (using well 6 as injector and wells 1 and 5 as producers).

In June 2006, Nuon announced plans for a new 1200 MW power plant at Eemshaven (where an existing natural gas fired power station is currently moth-balled). The Magnum project will use Shell's coal gasification technology which is also well suited to co-firing with biomass and could be fitted with CO_2 capture relatively easily. A decision on this will be made in mid-2007 with first production of electricity in 2011. RWE is also reported to be considering construction of a 1600 MW coal-fuelled power station at Eemshaven or somewhere else in the province of Groningen. It seems likely that CO_2 capture and storage would have to be part of such a scheme in order to avoid a large rise in national emissions. In both this and the Nuon case, captured CO_2 would probably be stored in disused oil or gas fields, either onshore or offshore. SEQ International has announced plans to build a 50MW oxyfuel pilot plant based on Clean Energy Systems concept (see below: USA) which would be in operation in 2009.

Shell's Pernis refinery is extracting concentrated CO_2, for supply to greenhouses for horticulture; this is used to replace natural gas which is currently burnt to enhance CO_2 levels indoors. This scheme uses an existing 85 km pipeline from Rotterdam harbour to Amsterdam which had been out of use for more than 25 years. A grid of smaller pipes has been constructed to distribute the CO_2 to the individual greenhouses. Deliveries of CO_2 started in 2005; 400 greenhouses are now being supplied and a further 100 are to be added. Emissions of 170,000 tonnes/year of CO_2 were avoided in the first phase with eventual capacity for 500,000 tonnes of CO_2/y. The gas distributor, NAM, is also developing a potential CO_2 storage project in the de Lier onshore gas field using CO_2 from the Pernis refinery; this could store CO_2 during the winter when the horticultural demand is lower.

6.1.3. UK

In contrast to the situation in Germany, over 80% of the new generating capacity announced in the UK by 2006 (RWE, 2007) will use fuels other than coal. The few coal plants that have been announced will fit CO_2 capture if/when the commercial and regulatory conditions are appropriate. In several cases the new plants will be able to burn up to 10% biomass in the fuel.

Centrica, the UK's major gas distributor, has acquired an option to participate in Progressive Energy's 800MW IGCC project on Teesside. This project will involve CO_2 capture together with a CO_2 pipeline and storage offshore in the North Sea, probably as part of an EOR project. It might be in operation by 2012. E.On is considering building a 450MW IGCC next to its existing gas-fired power station at Killingholme. The project would be built in phases - the IGCC itself first; this could be running by 2011; CO_2 capture could be added later, depending on the commercial and regulatory environment, with the CO_2 pumped through existing gas pipelines to storage in a depleted gas field under the North Sea. A feasibility study was started in 2006. E.On has also recently announced plans to build two new 800MW coal-fired units with supercritical boilers at its Kingsnorth power station at a cost of US$2000M. These units would have thermal efficiency of better than 45%. At some later date, the CO_2 produced by these new units would be captured and stored underground. E.On is also testing oxyfuel combustion at its technology centre at Ratcliffe.

RWE plans to install a 1600 MW coal fired power stations with supercritical boilers at Tilbury at a cost of US$2000M, with generation starting by 2013. These would be designed to accommodate CCS at a later date - RWE has indicated that it is looking to government to provide the necessary long-term and stable investment conditions to justify the investment. RWE has also announced that it is investigating the feasibility of replacing the Blyth power station with a new 2400MW coal-fired station using supercritical boilers which could also have capture fitted later.

Scottish and Southern Energy (SSE) plans a retrofit of CO_2 capture at its Ferrybridge power station in conjunction with fitting a new 500MW supercritical boiler and improved steam turbine. The design would facilitate subsequent deployment of post-combustion CO_2 capture equipment. Front-end engineering design work began in 2006 and investment decisions are to be taken during 2007. The plant could be in operation in 2011/12. It is estimated to require an investment of around US $500M; post-combustion CO_2 capture equipment would require a further US $200M.

Powerfuel plc plans to construct a 900MW IGCC at Hatfield, South Yorkshire which could be operating by 2012, with CO_2 piped to a North Sea field for storage. As with the Teesside plant, the promoters expect several plants in the area to want to capture CO_2 in future which could become the basis for a CO_2 pipeline network. For example, ConocoPhillips has announced it will build a new CHP plant at Immingham, only 60km from Hatfield, to serve its refinery and Total's Lindsey refinery – this may use gasification technology with CCS.

Other UK electricity companies have also expressed interest in CCS: Scottish Power will conduct a feasibility study of capture at its Longannet and Cockenzie power plants with storage in nearby coal seams, and Progressive Energy also has plans for an IGCC in South Wales.

6.1.4. Norway

In 2006, the Norwegian government and Statoil announced an agreement to establish a full-scale CCS project in conjunction with the installation of a combined heat and power plant at Statoil's Mongstad refinery. The first stage, which will be in place when the cogeneration plant starts to operate in 2010, will capture at least 100,000 tonnes of CO_2 per year; capture of all the CO_2 may take place by 2014. Statoil have also been required to prepare plans for CO_2 capture from the reformer and cracker units at the refinery. A company has been set up at Mongstad, 20% owned by Statoil, with a substantial investment by the government to develop technology; Vattenfall has recently announced it will participate in this test centre.

Norway already leads the world in CO_2 injection at the Sleipner field. A second Norwegian project, Snøvhit, will also store CO_2 in an aquifer, starting in 2007. Shell and Statoil have announced plans for an 860 MW NGCC power plant at the Tjeldbergodden methanol factory; this will include post-combustion CO_2 capture; the CO_2 may be piped to the Draugen field and later the Heidrun field for EOR starting in 2011, providing sufficient government support is obtained. Statoil and Shell are seeking state aid for the US$1500 million plant. Naturkraft AS (a joint venture of Statkraft and Norsk Hydro) is building a new NGCC at Kårstø; if economically feasible, this may be fitted with capture equipment in 2011/2 for EOR, possibly in the Volve field.

An international group, including Eramet (France), Alcan (USA), Norsk Hydro and Tinfos, is seeking bids for construction of a 400 MW coal-fired power plant to be built in western Norway. This will utilize CO_2 capture technology developed by the Norwegian company Sargas based on use of pressurised fluidised bed combustion. The plant itself will cost approximately US$700 million. 95% of the CO_2, as well as NO_x, will be captured and 2.6 million tonnes/year of CO_2 will be piped or shipped to offshore oil or gas fields. Construction of the project is expected to start in 2008, with production beginning in 2011.

6.1.5. Canada

SaskPower has announced plans for a 300 MW lignite-fired power plant to be built by 2012 which would capture CO_2 for use in EOR. SaskPower, Babcock & Wilcox Canada and Air Liquide will jointly develop the CO_2 separation technology for this project which will be located beside the existing

Shand Power Station near Estevan. A decision on the project will be made following completion of a feasibility study in mid-2007; the plant should start operating in 2011 and be fully online by 2012. It will supply 8000t/d of CO_2 to the Weyburn and Midale oil fields for EOR.

The flagship of Canadian work on CCS is the Weyburn/Midale project, which is a demonstration of CO_2 storage by adding a research component to Encana's CO_2-EOR project. The CO_2 is a by-product of the gasification of coal at Dakota Gasification's plant in Beulah, USA. Currently, approximately 5500 t/d of CO_2 are injected with a further 1300 t/d of gas and CO_2 recycled from the produced oil. Phase 1 of the monitoring project ran for 4 years until 2004. The second phase of the Weyburn monitoring project had become stalled in 2006 as government, industry and researchers negotiated how to share the project's results but recently field work has resumed. Other commercial CO_2-EOR projects in Canada also plan to use captured CO_2. Apache's Zama field uses acid gas injection for EOR and CO_2 storage.

A CO_2-ECBM project has been announced by Suncor Energy Inc. It is proposing to conduct a pilot project 20 kilometres south of Drayton Valley, Alberta. This will involve drilling a CO_2 injection well and a production well into coal beds.

Canadian plans for CCS are thus centred around supplying CO_2 for EOR, so it can be expected that these projects have a good chance of proceeding, if oil prices stay at current levels, even without government intervention.

6.1.6. Japan

Despite an early start on CO_2 capture R&D, no full-size CCS projects have yet been proposed in Japan. Mitusbishi Heavy Industries have developed a family of novel solvents for post-combustion capture; one of these, KS-1, has already been applied in a commercial urea plant capturing 200t/d of CO_2. A long term demonstration project also took place in 2006 in a side stream at J-Power's Matsushima coal-fired power station using KS-1 to capture 10t of CO_2 per day (other post-combustion pilot plants are in operation in Canada and Denmark). Testing of pre-combustion capture has been undertaken at a pilot plant at Wakamatsu. Japan is also a partner in the Callide oxyfuel power plant (see below, Australia).

The Research Institute of Innovative Technology for the Earth (RITE) carried out a monitored injection of 10,400t of CO_2 into an aquifer at Nagaoka in Niigata Prefecture between July 2003 and January 2005. A notable event during this experiment was that an earthquake occurred without disturbance of the stored CO_2. A CO_2-ECBM test has also been completed at Yubari.

6.1.7. Australia

Several CCS projects have been proposed in Australia. Chevron's Gorgon project will reinject CO_2 (separated from produced natural gas) into an aquifer at a rate of 2.7M tonnes/year. It was planned that this would begin operating in 2009 but there is now doubt about this date because of delay in receiving permission to build the associated LNG plant. Recently the government has provided financial support for the Gorgon LNG project.

An IGCC project is being developed by Stanwell Corporation - the 100MW ZEROGEN demonstration plant is intended to be the world's first demonstration of base-load electricity generation from integration of coal gasification with CCS. CO_2 would be transported by pipeline for storage in a deep saline aquifer in the Denison Trough in Central Queensland. Two wells have been sunk so far; a range of scientific tests are planned in which water and, possibly, small quantities of CO_2 will be injected to determine the suitability of the formation for storing CO_2. Shell is contributing advice and technical support on geological aspects of the project. Construction of the plant could start in 2008 with demonstration beginning in 2011. The project has applied for federal government funding under the Low Emission Technology and Abatement Programme as well as state funding.

An oxyfuel power plant at Callide, Queensland may also involve storage of CO_2 in the Denison Trough. This is a joint Japanese/Australian project. A retrofit demonstration of oxyfuel combustion on one 30 MWe unit at the coal-fired Callide A power plant is planned to begin operation in 2009 with CO_2 storage starting in 2010.

BP and Rio Tinto have announced plans for a power generation project at Kwinana in Western Australia involving CCS based on gasification of coal at a cost of about US$1700M. This would capture 4 million tonnes of CO_2 per year for storage. Feasibility studies were started in 2007. For the project to be competitive, it would be necessary for there to be supportive policy and regulatory environments. Providing the project is commercially viable, a final decision on it could be made in 2011, with the plant coming into operation 3 years later.

The Otway Basin Pilot Project aims to demonstrate monitoring and verification of CO_2 storage under Australian conditions. It involves the storage of up to 100,000 tonnes of CO_2 starting in mid-2007. CO_2 will be extracted from a nearby natural gas field and transported 2 km through a pipeline. Injection is due to start in mid-2007 with breakthrough at the monitoring well expected between 6 and 9 months later. A comprehensive atmospheric, geophysical and geochemical monitoring programme will be deployed. The government is providing support for this US$25M project.

At least 2 coal-to-liquids projects have been proposed in Victoria. The Victoria Power and Liquids Project plans to avoid nearly all emissions of CO_2 by capturing it for storage in deep geological formations in the offshore Gippsland and Bass basins. An independent assessment of the long-term CO_2 storage capacity of these basins is being undertaken. A project organised by Anglo-American with Shell (called Monash Energy) will investigate the feasibility of coal-to-liquids technology and may develop a production plant; plans for CCS will be established at the same time, depending on the regulatory regime.

6.1.8. USA

Clean fossil fuel technology is an important part of the US DOE's technology programme. A major element of this is FutureGen, a 275MW coal-fuelled IGCC demonstration of electricity and hydrogen production with CO_2 capture for storage. It is expected to cost US$1000M of which two-thirds will be provided by DOE. A preliminary design has been produced and a short list of 4 candidate sites announced. The final selection will be made in the second half of 2007, with construction due to start in 2009. The plant is expected to be on-line around 2012.

BP has announced plans for a 500MW IGCC with CO_2 capture to be built at its Carson City refinery in partnership with Edison Mission Energy; this would use petcoke as fuel and would supply CO_2 for EOR.

AEP, the largest electricity generator in the USA, hosts DOE's largest US geologic storage project in a deep saline formation at its Mountaineer Plant in West Virginia. This project involves geological characterization, and design of a CO_2 injection well and preparation of permits. AEP plans to capture up to 100,000 tons of CO_2 per year at the Mountaineer plant using Alstom's chilled ammonia solvent in a post-combustion process. Providing this demonstration is successful, a full-scale project using this technology will take place at a 450 MW power plant in Oklahoma; 1.5 million tonnes of CO_2 a year will be captured for supply to enhanced oil recovery in 2011.

AEP has also signed memoranda of understanding with Babcock & Wilcox (B&W) to use its oxy-coal technology. B&W will conduct a test of the technology in 2007 in its 30MW test facility. Following this, AEP and B&W will conduct a feasibility study of a retrofit application after which detailed design engineering and construction estimates will be carried out. This technology is expected to be in service on an AEP plant between 2012 and 2015.

Alstom has announced construction of a pilot plant to demonstrate the use of chilled ammonia for capturing CO_2, using a 1% side-stream from the boiler flue gas at We Energies power plant in Pleasant Prairie, Wisconsin. It is claimed the process reduces the energy required for capture as well as the cost. The pilot project will be commissioned in mid-2007 and operated for about one year.

TXU Corporation has announced plans to build 11 new coal-burning power plants in Texas by 2011 (total capacity of 9.1 GW). These new units are to be capture-ready, which means allowing enough space to install the capture equipment when it becomes available and economically feasible. Similar announcements have been made in Florida, which is home to one of 7 US regional sequestration partnerships (made up of state agencies, universities and private companies). An IGCC has been proposed for construction at Nueces in Texas; this should be operating by 2012; it would have the capability to add CO_2 capture for EOR at a later date.

The state of Illinois has issued a Request for Information relating to the construction and operation of a CO_2 pipeline. The pipeline would be part of a $775M plan involving construction of 10 coal gasification power plants in central and southern Illinois which will be completed by 2017. The 220 km pipeline would transport CO_2 captured at these plants to oil fields in south-eastern Illinois for enhanced oil recovery.

PacifiCorp has been selected by the Wyoming Infrastructure Authority to carry out a feasibility study for a 500 MW IGCC which would come online in 2014; this would have potential for capturing about 60% of the CO_2 produced by an unmodified unit, if PacifiCorp can find customers for the CO_2.

A small private company proposes to construct a 700MW coal-fed IGCC power station with CCS at Wallulai in Washington State; the CO_2 would be injected into underlying basalt rock reducing CO_2 emissions by 65%. The plant could be operating by 2013. Initial financial support will be provided by a division of Edison International. Pacific Northwest National Laboratory plans to drill 1200m wells on the site in 2007 to test the storage capability by injecting several thousand tonnes of CO_2.

Clean Energy Technologies is developing an oxy-combustor fuelled by natural gas. This is based on rocket engine technology which produces a high-temperature, high-pressure gas to drive a multi-stage turbine to generate electricity. The process recycles steam rather than flue gas to moderate combustion temperature. The technology is being developed initially for supplying CO_2 to small oil fields for enhanced oil recovery.

More than 20 small-scale CO_2 injection projects (i.e. with capacity of order tens of thousands of tonnes of CO_2) are planned across the country by the regional partnerships. Collectively these partnerships have identified capacity for storage of 82 Gt of CO_2 in oil and gas reservoirs and between 919 and 3378 Gt in saline formations. DOE aims to initiate at least one large scale injection project (more than 1 million tonnes/year) by 2011. In view of the rate of announcements, there are probably other US proposals which have not been mentioned here.

6.2. Ownership of the technology

Design and construction of power stations can be performed by many engineering contractors but some of the additional processes involved in capturing and storing CO_2 are only available from a limited number of technology licensors. This need not inhibit transfer of the technology but in some instances there has been concern about the cost of licensing and its effect on technology transfer, especially to developing countries. The technology licensors are all working on improving their designs, especially in respect of CO_2 capture, so this paper only provides a snapshot of the information in the public domain at the time of writing.

Various processes using proprietary solvents and processes have been developed with improved performance and to overcome some of the problems of capturing CO_2. Some examples of commercial chemical solvents are shown in Table 6.1. Others are under development.

Table 6.1 Examples of chemical solvents used for removal of CO_2

Solvent	**Proprietary name**	**Process vendors**
Monoethanolamine	AmineGuard FS/Ucarsol Econamine	UOP/Dow, USA Fluor, USA
Methyldiethanolamine	aMDEA	BASF, Germany Elf, France

		UOP, USA
Proprietary mixture of amines	KS-1	MHI, Japan
Potassium carbonate	Benfield	UOP, USA

Commercial processes for post-combustion capture are available from ABB Lummus Crest, Fluor, Kansai Electric Power/MHI.

Physical solvents are used with gas streams having high CO_2 partial pressure and/or high system pressure. Some of the proprietary physical solvents currently available are listed in Table 6.2.

Table 6.2 Some physical solvents used for removal of CO_2

Solvent	**Proprietary name**	**Process vendors**
Methanol	Rectisol	Lurgi and Linde, Germany
N-methyl-2-pyrolidone (NMP)	Purisol	Lurgi, Germany
Dimethyl ethers of polyethylene glycol	Selexol	Union Carbide, USA

In a gasification system, sulphur-containing compounds, such as H_2S, are removed before the CO_2 separation; this can be done with a chemical solvent developed specifically for this task (Table 6.3) or Selexol or aMDEA may be used.

Table 6.3 Some chemical solvents developed for removal of sulphur compounds

Solvent	**Proprietary name**	**Process vendors**
A mixture of tetrahydrothiophene 1,1-dioxide and water	Sulfinol	Shell, Netherlands
Severely hindered amine	Flexsorb	ExxonMobil, USA

There are various types of gasifier, each of which may be configured in different ways, but the front runners include gasifiers from GE (previously Texaco) and Shell. Siemens has recently acquired a small company, Future Energy, which has the rights to a gasifier. Another gasifier in Germany is well suited to low rank coals, which are increasingly being used in many parts of the world. Gasifiers are also under development in China.

For oxyfuel combustion, no supplier has yet installed a full-size power plant using this equipment although there are several groups developing capability in this technology e.g. Doosan-Babcock, Jupiter, Vattenfall/Alstom, Clean Energy Systems. There is not yet a clear picture of how such equipment would be supplied to users but it is likely to be licensed to plant contractors.

Advanced, high efficiency, gas turbines are not available for combusting fuel with high H_2-content at present as would be required in IGCC with capture. In particular, the current premix combustors, developed to achieve low NO_x levels, are limited to a maximum H_2 content of 10% due to the potential for flashback (Moliere, 2004). Consequently the older type of diffusion burner has been used but this has the disadvantage that NO_x levels increase fast with combustion temperature thereby limiting efficiency. GE has mapped the combustion conditions in a 6FA turbine burning fuels with high H_2 content (Shilling and Jones, 2004) and is working on developing a premix burner for use with this type of fuel. Siemens and Alstom are understood to be working on similar developments. One advantage of using the older type of gas turbine is that experience with IGCCs has shown these are more reliable.

Industrial experience with gas compression is available to design and manufacture compressors for CO_2 but the large scale of these machines and the conditions of operation mean this is a specialised design task; there are only a few compressor manufacturers worldwide able to provide suitable machines.

Injection of CO_2 is carried out today by the oil industry in USA and Canada and has been performed in pilot projects in many other countries including China and Brazil. Detailed monitoring of the behaviour of CO_2 in the reservoir is still relatively rare so the dissemination of knowledge for predicting storage performance is limited at present. Similarly, risk assessment procedures are still under development. There are 5 commercial projects in which CO_2 is injected for storage at present but several smaller injections (i.e tens of thousands of tonnes of CO_2 per year) are underway or planned for the next few years to build local experience with this technique.

7. Initiatives influencing use of CCS

There is no commercial incentive for use of CCS at present so the financial and regulatory frameworks that governments establish will have a major influence on the willingness of industry to invest in the new technology. This chapter will review means of support[2] that are available or under development. The focus is on Annex 1 countries that have ratified the Kyoto Protocol and are thought to be serious about implementing CCS but the plans of a few, key countries that have not ratified the Protocol but are interested in CCS are also examined. Although much of the activity is directed at domestic activity, there is also interest in financing CCS projects in other countries, particularly by use of the Clean Development Mechanism (CDM).

Major programmes of publicly-funded R&D have been underway for some years in North America, Europe, Japan and Australia. These were intended to gain experience, improve the technology and reduce risk. Commercial organisations have funded a significant part of this work. More strategic plans are now developing, especially in the EU and the USA – for example the European Commission has recognised the need to support several full-scale CCS projects; US DOE's regional partnerships have provided the basis for developing strategic plans for the technology (US DOE, 2007). A few developing countries are also starting to take an interest in the technology.

[2] This concentrates on demonstration of full-size plants; there is also a multiplicity of smaller research and development activities but, because of the great number of projects, these are not discussed specifically.

7.1. Financing of CCS projects

Without an appropriate commercial framework, fossil-fuelled power plants will not be fitted with CCS. Possible methods of paying for CCS include the Flexible Mechanisms of the Kyoto Protocol which may be used by Annex 1 Parties to meet their emission reduction targets. The 3 Flexible Mechanisms are: International Emissions Trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI). The aim of the Flexible Mechanisms is to lower the overall cost of achieving emission reduction targets by allowing Annex 1 Parties to access cost-effective opportunities to reduce emissions in other countries. While the cost of limiting emissions varies considerably from region to region, the benefit for the atmosphere is the same, wherever the action is taken.

In addition, funding for CCS projects might be provided through national emissions trading, by direct support for projects and or by (avoidance of) carbon taxes.

7.1.1. Emissions Trading

An emission trading system has been in use in the USA in respect of sulphur emissions for some years. The European Emission Trading System (ETS) is the first government-organised system of trading CO_2 allowances and is used here as an example of the features of such systems. It is based on the following principles:

- Setting caps on emissions, on a national basis.
- Initial focus on CO_2 from big industrial emitters.
- Allocations of emission allowances, which can be traded.
- Implementation in phases, with periodic reviews and opportunities for expansion to other gases and sectors.
- Strong compliance framework.
- Use of CDM and JI and possibility to establish links with compatible schemes elsewhere.

At the heart of the ETS is the common trading *currency* of emission allowances. One allowance represents the right to emit one tonne of CO_2. The *cap* on the number of allowances creates the scarcity needed for a trading market to emerge. Companies that keep their emissions below the level of their allowances are able to sell their excess at a price determined by supply and demand at that time. Others have a choice of taking steps to reduce their emissions or buying the extra allowances at the market rate. This should ensure that emissions are reduced in the least-cost way. The ETS is now in its first phase of operation; the second trading period will run in parallel with the first commitment period of the Kyoto Protocol.

7.1.2. Clean Development Mechanism

The CDM is a project-based mechanism. It allows Annex 1 countries to implement projects that reduce emissions in countries which are not in Annex 1. In return they receive certified emission reductions (CERs) which can be counted towards their emissions targets under the Kyoto Protocol. Such projects are intended to help the host country develop in a sustainable manner. The CDM is expected to promote the transfer of environmentally-friendly technologies.

The possible acceptance of CCS projects under the CDM has generated substantial debate in the CDM Executive Board (which administers the scheme) and in the Conference of the Parties to the UNFCCC. Three CCS projects were put forward to the Executive Board (EB) as potential CDM projects in 2005; the methodologies for accounting for these projects were considered by the EB in 2006, which gave much attention to the issue of potential seepage from CCS sites. In particular it raised a number of general questions concerning:

- Physical leakage[3], including questions about site selection and measurement, although the EB did recognise that deciding on an acceptable level of leakage goes far beyond typical CDM methodological issues;
- Responsibility for seepage and methods of accounting for it;

[3] The EB used the term "seepage" to refer to physical leakage.

- Project boundary issues – these appear to go beyond current CDM procedures, especially in questions about which reservoirs would be used.

At the second meeting of the Conference of the Parties to the Kyoto Protocol (CMP.2) in Nairobi in 2006, a variety of views were expressed amongst Annex 1 and non-Annex 1 countries about the acceptability of CCS as project activities under the CDM. A number of countries were clearly in favour of CCS, including Australia, EU, Canada, Iran, Japan, Kuwait, Norway, Qatar, Saudi Arabia, UAE. Furthermore, some countries appeared to be neutral, such as: Bangladesh, China, India, New Zealand. However, certain countries opposed the proposal, especially: the Association of Small Island States (AOSIS), Brazil, Switzerland. Jamaica noted there were many uncertainties with respect to the technology and also that its limited geographical application would exclude many countries from using it. Argentina expressed concern at the "hasty" amendment of the London Protocol to allow for storage in sub-seabed formations. Brazil expressed fears that CCS would operate on a scale never anticipated by the negotiators of the Kyoto Protocol, which would "crowd out" other CDM projects.

In addition, several environmental non-governmental organisations (ENGOs) wrote to the heads of the EU delegations opposing acceptance of CCS as CDM activities in the first commitment period because of concerns about lack of appropriate safeguards, lack of a strong regulatory framework to minimize the risks and liability to future generations and the environment, and the potential to compromise the sustainable development objectives of the CDM.

The conclusion of CMP.2 was to put off a decision about whether to accept CCS in geological formations as a possible CDM project activity. A number of unresolved technical, methodological, legal and policy issues relating to CCS as CDM projects were recognised. The Subsidiary Body for Scientific and Technological Advice (SBSTA) was requested to prepare recommendations about acceptance of CCS in the CDM in time for CMP.3 in 2007, with a view to taking a decision at CMP.4 in 2008.

The results of this meeting give the impression that delegates participating in the CMP.2 discussions were unaware of IPCC's 2006 Guidelines, the IPCC Special Report on CCS and the understanding that went into them. Instead the Parties seem to have started from scratch to build up a body of basic information on storage of CO_2 without reference to IPCC's work. However, some of the issues raised were not covered by the 2006 Guidelines, such as those concerning management of the storage facility. That is something which should be handled through development of international standards for management of CCS facilities, which are not yet available.

7.1.3. Joint Implementation

The other project-based mechanism of the Kyoto Protocol is Joint Implementation (JI). Under JI, an Annex 1 Party may implement a project to reduce emissions in another Annex 1 country; for this it would receive emission reduction units (ERUs) which it can use towards meeting its own Kyoto target. In order for countries to take part in JI projects they must appoint Designated Focal Points and adopt national guidelines and procedures for approving JI projects. Most of the countries which have done this are members of the European Union (although 6 members of the EU have not done so) together with 6 others. Little has been reported about use of CCS under JI.

7.1.4. Carbon tax

A carbon tax has been considered in several countries as a way of reducing CO_2 emissions. In its simplest form it would be a tax on energy sources which emit CO_2. It is theoretically favoured by some economists because it is a tax on the externality of climate change, so could be seen as directly acting as a corrective measure. In practice, carbon taxes are often directed at specific sources (such as large industry or offshore sources). Carbon taxes have been applied in Sweden, Finland, the Netherlands, and Norway – in that case, it had the side-effect effect of funding the Sleipner CO_2 storage project.

7.1.5. Other international financing mechanisms

The Global Environment Facility (GEF) helps developing countries fund projects (through grants) to protect the global environment and promote sustainable livelihoods in local communities. The GEF is funded by donations from 32 nations. In respect of the mitigation of climate change, GEF takes a long-term perspective to reducing GHG emissions. It uses its grants to foster economic growth and sustainable development by enabling the energy markets to operate more efficiently and to move the country concerned away from carbon-intensive technologies. In particular, GEF supports improving energy efficiency, promoting renewable energy, reducing the costs of low-GHG-emitting energy technologies, and sustainable transportation and helping markets operate more effectively. The low-GHG-technology strategy builds on the idea that providing developing countries with early experience in new technologies in niche applications will contribute to the expansion of the demand for these technologies. This, in turn, should lead to increased supply and reduced cost. It is not clear that GEF recognises CCS as an appropriate technology for its support.

7.2. Initiatives of countries that have ratified the Kyoto Protocol

Certain countries seem to have serious intentions of implementing CCS during the first commitment period. At the start of 2007, the European Commission announced plans for European energy policy, which included specific proposals for supporting CCS – this will be discussed first, followed by the plans of some other countries.

7.2.1. European Union

The European Commission put forward a Strategic review of Energy Policy in January 2007. CCS is a major feature of these plans. The Commission has indicated to the European Parliament (EC, 2007) that it will promote Sustainable Fossil Fuels by establishing a favourable environment for action and by supporting the implementation of CCS technology. Although the Communication concentrates mainly on use of coal, the Commission notes that CCS should be applicable to other fossil fuels, especially gas.

The Commission expects that the ETS will provide the primary incentive for investments in CCS through stable and strong prices for CO_2 allowances. However, the Commission has recognised that it is not yet clear how the ETS can be configured to provide price signals suitable for encouraging long-term investment in new plant. Although such measures would only come into use after 2020, they would have to be adopted sufficiently far in advance so as to provide clear signals for investment decisions. They would also have to be compatible with measures already in place to encourage use of renewable energy. Once the commercial viability of CCS had been demonstrated, it would be necessary for there to be an appropriate framework so that new coal-fired power plants built after 2020 operate with CCS. This would include rapidly retrofitting capture-ready plants built before then.

In autumn 2007, the EC's Environment Directorate will list policy options for regulation of CCS including the ETS. These options will take account of the forthcoming Water and Waste Directives, because both of these could affect the use of CCS. This may lead to a Directive on regulation of CCS but it is too early to be sure what this might contain. In the meantime, the UK is developing national regulations and permitting for CCS projects which should help to inform the EC[4].

7.2.1.1. European Union policy on CO_2 capture and storage

The Strategic Energy Review was accompanied by plans for action in 7 specific areas including CCS (EC, 2007) - without such technologies the Commission expects that Europe will be unable to meet its greenhouse gas emission objectives. The 7 areas are:

- Internal energy market.
- A new European internal energy policy
- Energy efficiency measures
- Renewable energy
- Near-zero emission fossil fuel power generation

[4] In 2005, UK submitted a report on "Developing Monitoring Reporting and Verification Guidelines for CO_2 Capture and Storage in the EU ETS". This identified issues arising from use of CCS that will be important when considering its inclusion in emissions trading schemes; it also presented key criteria by which interim guidelines for monitoring reporting and verification may be prepared. Proposals for detailed requirements for monitoring and reporting of CCS in emissions trading are now under development.

- Nuclear electricity
- Establishing a common external energy policy.

The main objective of the proposals is to reduce EU greenhouse gas emissions by 20% by 2020 compared with 1990 levels. This was agreed at a meeting of the European heads of state in March 2007. The plan also recognises the need for international action on climate change and indicates that, when (and only when) an international commitment is achieved, the EU will increase its target to 30% reduction by 2030 and 60-80% by 2050. Germany has indicated that it will set itself a goal of 40% reduction by 2030 if the EU adopts the 30% reduction target. The depths of these reduction targets will have great relevance for the use of CCS in the period concerned.

In 2007, the Commission will start work to design a mechanism to stimulate the construction and operation by 2015 of up to 12 large-scale fossil fuel demonstration power plants in the EU and provide a clear perspective as to when coal- and gas-fired power plants will need to install CO_2 capture and storage. The Commission believes that, in principle, by 2020 all new coal-fired plants should be fitted with CO_2 capture and storage and existing plants should then progressively follow the same approach.

7.2.1.2. European Emissions Trading Scheme

In the first trading period, Member States drew up national allocation plans which gave each installation in the scheme a number of allowances. The first trading period runs from 2005 to 2007. During this period, the ETS covers only CO_2 emissions from large emitters in the power and heat generation industry and in selected energy-intensive industrial sectors: combustion plants, oil refineries, coke ovens, iron and steel plants and factories making cement, glass, lime, bricks, ceramics, pulp and paper. Plants below a certain size in each sector are not included in the scheme. CO_2 capture and storage was not accepted as a means of reducing emissions in the first trading period. If there had been any CCS projects, they would have been treated as if the CO_2 were in fact emitted.

At least 95% of the allowances were allocated to installations free of charge in the first period and, it is expected, at least 90% will be so allocated in the second period, although the Commission is being stricter on the level of the caps in the second period. Only plants covered by the scheme are given allowances but anyone is free to buy and sell allowances in the market.

Negotiations are now underway for the second period. The Commission will amend EU environmental legislation after a public consultation in 2007 and expects to include CCS activities in the ETS when revisions to it are proposed in 2007. It is likely that, for the second period, CCS will only be available for credits in certain countries in the EU - individual member countries will have to "opt in" any CCS projects that they wish to be included in the second period (i.e. countries which want to use CCS will have to identify the specific CCS projects to be included, as well as propose methodologies for monitoring and reporting each project, for permitting, assessing environmental impact and assessing any market distortion). The European Commission is keen that this should happen and is looking to a Member State to lead the way. The UK has responded by commissioning consultants to develop proposals on how to take this forward and is treating the Progressive Energy/Centrica IGCC as the first CCS project to be "opted in" to the ETS. At least one country, Poland, is opposed to inclusion of CCS in the second period of the ETS. The Commission expects that CCS will be accepted as a standard emissions control measure in the third period of the ETS so it could then be used as widely as any other measure. It is intended that the ETS should be consistent with national reporting of emissions so the reporting guidelines ought to be compatible with IPCC Guidelines - at present the European guidelines are still under development so the final form is not yet known.

A major problem for any capital project, such as CCS, is that the ETS can only guarantee allowances for a limited period (4 years in the case of the second period). In order to encourage more capital investment, it would be important for allowances to be valid for a longer period. It appears that this may be achieved in the third period.

It is expected that UK, Netherlands and Germany amongst others will want to qualify CCS projects in phase 2 of the ETS. Norway, Iceland, Liechtenstein and Switzerland have agreed in principle to join the ETS.

7.2.1.3. European support for demonstration projects

Through the "Zero Emission Power Plant Technology Platform" (ZEPP TP), major energy companies involved in coal-fired power generation have announced plans for 10 to 12 large-scale demonstration plants involving various ways of integrating CCS in coal- and gas-fired power generation. Such plants will need to be operated for at least five years before the technologies are considered to be fully demonstrated and ready for investment as standard plant, which the Commission sees as happening in/after 2020. So the Commission will increase funding substantially for R&D in CCS; it wants Member States to show a similar commitment to R&D and demonstration. The 7th Framework Programme is expected to spend about €350M over 7 years on clean coal technology and CCS but this will depend on member states funding a considerable part of the work.

The Commission will determine the most suitable way to support the design and construction of up to 12 large-scale demonstrations of CCS in commercial power generation for operation by 2015. It will also need to examine ways of supporting the operation of these plants because, at present, this would not be allowed under rules limiting State Aid to power generation.

During this period, it is likely that many new power plants will also be constructed, to replace existing coal-fired capacity - if these were to be built without CCS, they might be difficult to retrofit later. Indeed, in expectation that CCS-equipped power plants would have higher costs than conventional power plants, some utilities might rush to build new power plants early, in order to avoid having to fit CCS. To avoid such a situation, the Commission plans to assess recent and planned investments to see whether new fossil-fuel power plant will be designed for the later addition of CCS. If it turns out that this is not the case, the Commission has indicated it would consider take legal steps to make this happen.

7.2.2. Germany

After COP-3 in Kyoto, the German government committed to reducing CO_2 emissions by 25% (its share of the EU-burden under the Kyoto commitment was -21%). In 2002 the government proposed a target of 40% reduction by 2020, providing other European countries aimed for a 30% reduction.

The German electricity industry expects to replace 40 GW of fossil fired power plants in the next 10 years, with another 35 GW over the following 10 years. As far as the electricity industry is concerned, use of CCS is dependent upon the government providing the necessary long-term and stable investment conditions. This will require acceptance of CCS projects in the European Trading System (ETS) in phase 2, as well as ratification of the amendments to the OSPAR convention to accept CO_2 storage.

The State Secretary of the German Environment Ministry made a very positive presentation on CCS at the first general assembly of the ZEPP TP held in September 2006. He indicated a need for CCS to become the standard for construction of new coal-fired power plant by 2020 at the latest. He pointed out the need for CO_2 storage to be safe, and for reduction in costs; construction of demonstration projects is needed by industry; government must design a regulatory framework for permitting CCS projects. The government is now developing a legal framework for CO_2 storage but would like to achieve a harmonized European approach, something which might delay progress with industrial CCS projects. The government-funded COORETEC R&D programme supports work on efficiency improvement as well as CCS and has an annual budget of €25M which is expected to increase to €37M by 2010.

7.2.3. Netherlands

For many years the Netherlands' strategy for meeting its Kyoto obligations has included a package of primary measures plus a number of reserve measures, in case the primary measures could not reach the agreed target. These reserve measures include use of CCS for process emissions not included[5] in emissions trading. The extent of emission reductions available from use of the reserve measures could be around 0.5 Mt CO_2 in the first commitment period, if they were introduced in 2007 but declining thereafter if delayed. A plan for this is being drawn up by the government taking account of legal, infrastructural and financial requirements.

An evaluation of progress towards its Kyoto targets in 2005 indicated that, under existing policy, the Netherlands was likely to meet its domestic emission reduction target during the first commitment period. A separate target for JI and CDM activities had been adopted but it is too early to know whether that target can be met.

The Cabinet decided in 2006 to invest in developing a more sustainable energy economy in order to be less dependent on fossil fuels in the future and to limit GHG emissions. As part of this, €250 M was allocated in connection with the decision to keep open the Borssele nuclear power station - the money will be used to double the CO_2 reduction from keeping the plant open (1.4M tonnes/y of CO_2) by funding energy efficiency measures, CCS and renewable energy. The government is talking to energy companies about obtaining a similar financial contribution from them. Some large demonstration projects with underground CO_2 storage are planned but there are differences of view about whether to use some of the depleted oil fields for storing Russian gas or for CO_2. Several years ago the government initiated the ORC (Offshore Re-injection of CO_2) project and is also supporting CCS development through the CATO programme.

As market players demonstrate increasing interest in CCS, the government will indicate how it intends to support them. Some funds will be available from the national budget for a transition to a sustainable energy economy, in order to stimulate CCS in electricity generation; an annual budget of €23M will be allocated at the launch of the scheme for Environmental Quality of Electricity

[5] No reserve measures are being prepared for companies participating in the emissions trading scheme because, once the emission ceiling has been established, reserve measures should not be needed.

Production in 2008. But the government is also the assessor of the environmental impact of underground CO_2 storage and recognises it needs to make this clear in the planned environmental impact assessment of demonstration projects. Ways of developing a quantitative target for CCS for the long term, for example 2020, are also being studied.

7.2.4. UK

The UK government commissioned a review of climate change from Sir Nicholas Stern, to assess the evidence and build understanding of the economics of climate change. This was reported in late 2006. It examined evidence on the economic impacts of climate change and explored the economics of stabilising greenhouse gas concentrations in the atmosphere. It then went on to consider the policy challenges involved in making the transition to a low-carbon economy. In a wide ranging review of mitigation options, the report noted that "even with very strong expansion of the use of renewable energy and other low carbon energy sources, hydrocarbons may still make up over half of global energy supply in 2050. Extensive carbon capture and storage would allow the continued use of fossil fuels without damage to the atmosphere, and also guard against the danger of strong climate-change policy being undermined at some stage by falls in fossil-fuel prices." This seems to have been well received in government but it is not yet clear how this recognition of the potential of CCS will be translated into policy.

In its 2006 review of Energy Policy, the government made various announcements about CCS:

- A first call for proposals under the Carbon Abatement Technology demonstration programme (worth US $20M) focussed on the pre-commercial demonstration of key components and systems to support carbon abatement technologies;
- Continued work with international partners to amend international legal frameworks, such as OSPAR and the London Protocol, to provide the legal basis for CCS;
- Develop proposals on appropriate regulations both to facilitate CCS and to ensure the environmental integrity of CCS activities;

- Continue work with international partners to develop the potential of CCS, including work with Norway and others to enable CCS in the North Sea, as well as the EU-China Near-Zero Emissions Coal initiative;
- Push for recognition of CCS within the EU ETS.

The Government believes that the next stage would be a commercial demonstration of CCS, if cost-effective. More work has been undertaken to determine the costs of such a demonstration project. A competition was announced in the 2007 Budget to develop the UK's first full-scale CCS demonstration, the result of which will be announced in 2008; the aim is that the plant would be operational early in the next decade. The UK also intends to develop a detailed regime for regulation of CCS, especially offshore. It will cover storage but not EOR as this is addressed by existing rules.

7.2.5. Norway

For a long time, Norway has advocated ambitious climate policies. The current government came into office in October 2005 with a mandate to develop environmentally friendly alternatives to hydropower. Use of natural gas in power plants provides an opportunity for Norway to make use of its large gas resource but this has to be done without an increase in GHG emissions. Norway aims to be at the forefront of using CCS as a means of meeting its Kyoto targets.

Norway introduced a carbon tax in 1991. This tax has varied over time and between sectors - it has been heaviest on gasoline and offshore sectors although several industries with relatively high emissions, such as metals production, are partially or totally exempt from the tax. The tax is amongst the highest such taxes in the world. However, as a policy measure, it is reported to have had only a modest influence on greenhouse gas emissions.

The Petroleum and Energy Minister has indicated Norway may spend US$600 million on the Mongstad test facility (see above). The government intends to establish "CO_2-chains" where CO_2 is captured, transported to oil fields and used to increase oil recovery. In this it has the support of environmental NGOs. It will cover the costs of transporting CO_2 from some of the onshore CCS projects to offshore reservoirs for storage and/or EOR. Negotiations are underway about the precise level of government support for these projects.

The national CCS programme has supported this technology for many years (US$ 77M was spent over 5 years to 2001); currently the CLIMIT programme supports R&D on natural gas power generation with CCS (budget in 2005 was US $16M). In 2006, the Minister of Petroleum and Energy announced plans to spend US $150M on CCS-related work in 2007.

UK and Norway are working together to draft regulations for the transport of CO_2 in the North Sea. They are also co-operating on a study of infrastructure in the North Sea, something which is becoming a pressing issue with the planned decommissioning of oil and gas production platforms and pipelines especially in the UK sector.

7.2.6. Canada

Since the 2005 election, the minority Canadian government has been trying to steer a course through Canada's domestic and international GHG commitments. Having announced the intention of not meeting its Kyoto targets, the government recently appears to have accepted the need to address GHG emissions, not least because the opposition pledged to make global warming a top issue, something that a majority of Canadians agree with (according to opinion polls), but the possibility of a change in government in 2007 adds to the uncertainty. Proposals to shut down all of Ontario's 7000 MW of coal fired generation by 2009 seem to have been put on hold, with only one station closed so far. Certain provincial governments have indicated they may regulate GHGs irrespective of whether the federal government does so.

A new environment minister was appointed in January 2007 who increased funding for alternative energy sources and conservation although many of these actions are similar to measures that were scrapped in the 2006 budget. The “ecoEnergy Technology Initiative” will be worth US$197 million; it will support research, development and demonstration of clean-energy technologies, including CCS, clean oil sands production and renewable energy. Priorities within the programme will be agreed with the Canadian provinces and industrial partners. However the government is still sceptical of the Kyoto Protocol, supports nuclear power and is not convinced about emission trading although, in November 2006, it was reported that Canada was investigating establishing its own domestic carbon market, which could later join the European ETS.

7.2.7. Japan

In May 2007, the Prime Minister announced a strategy for halving greenhouse gas emissions by 2050. He proposed principles for international action beyond 2013:

- All major emitters must participate and move beyond the Kyoto Protocol to reduce global emissions.
- A diverse and flexible framework is required, taking into consideration the circumstances of each country.
- The framework must achieve compatibility between environmental protection and economic growth by utilizing energy conservation and other technologies.

The prime minister also proposed the creation of a financial mechanism for aiding developing countries as well as a national campaign for reducing GHG emissions. This was seen by commentators as an indication that the Cabinet Office was beginning to play a major role in making environmental policy.

The Ministry of Economy, Trade and Industry (METI) announced plans in 2006 to establish CCS facilities in Japan and abroad. The aim was to reduce emissions from factories and power plants[6] by 200 million tonnes annually (about a sixth of current CO_2 emissions) – half of this in Japan. METI is

[6] 161 major sources have been identified as producing 539 Mt/y CO_2.

organising research, building facilities and developing the necessary legislation with the aim of making CCS one of the main methods for reducing emissions. It intends to take the lead in developing the technology and establishing demonstrations until the cost of reducing emissions is cut to around US$30/tonne of CO_2. METI will also support on-site research and safety assessments. Utilizing CCS technology in Japan had previously been considered difficult due to the lack of suitable land and expensive land prices. Underground storage capacity has been estimated at 150 Gt (of which 5.2Gt is in anticlines from which samples have been obtained). Pilot injection projects should take place between 2008 and 2015 and a practical storage project is envisaged in 2016.

The Environment Ministry has said it will propose legislation to the Diet to enable industry to implement sub-sea storage in aquifers (permission will be required from the environment minister, to ensure the quality of each project). The legislation will provide the framework for implementation of storage projects on a commercial basis. It is also designed to provide legal support for the Nagaoka project. It is envisaged (Japan Times, 5 February 2007) that CO_2 would transported by ships to offshore platforms for injection. Plans for other drilling in offshore areas used for CO_2 storage would also have to be cleared by the minister. The government would be able to impose fines of up to US$ 90,000 for transgressions of the law on storage. The Japanese government also has plans to support use of CCS in developing countries but these have been delayed by the CMP.2 decision on the CDM.

7.3. Initiatives of countries that have not ratified the Kyoto Protocol

7.3.1. Australia

The federal government has committed about US$1700 M to combating climate change - this will be used for emissions management, international engagement, addressing the risks, and understanding the science. Climate change initiatives worth approximately US$430M were included in the 2004 Energy

White Paper to support industry-led demonstrations of technologies through the Low Emissions Technology Demonstration Fund.

The Queensland government has earmarked US$ 250M to develop clean coal technology, particularly the ZEROGEN project. A recently announced US $ 350M plan to cut Queensland's greenhouse gas emissions includes a US$8.5M fund to assess the capacity for CCS at two sites in Queensland – the Denison Trough and the Galilee Basin. The government has been criticised by WWF for, at the same time, allowing construction of large coal-fired power stations without CCS.

Other State governments have also announced support for their own projects – in Victoria, a total of US $67.5M is being provided from State and Federal programmes towards the cost of a pilot at the Hazelwood power plant for drying brown coal which will also involve some work on post-combustion CO_2 capture. Other funding from Victoria is supporting demonstration of the gasification of brown coal, projects which are said to be able to incorporate CCS at a later date. New South Wales is providing US $18M support for a CCS project.

The announcement of several CCS projects has necessitated development of a regulatory framework for CCS. Some states already have legislation/regulations that cover aspects of CCS. For example, the South Australian Petroleum Act 2000 and the Queensland Petroleum and Gas (Production and Safety) Act 2004 provide for transport by pipeline and storage in natural reservoirs of substances including CO_2, regardless of source. The Petroleum (Submerged Lands) Acts provide a mechanism for authorising and regulating capture and offshore storage of CO_2 separated from the petroleum stream in a licence area, as part of the integrated petroleum operations of the licensee. CCS streams from other sources (e.g. from a power station onshore or other offshore petroleum operations) cannot at present be authorised for offshore storage.

Australia is planning to set up a carbon trading market by 2012, which might join the ETS.

7.3.2. USA

The USA has set itself a national goal of reducing GHG intensity by 18% from 2002 to 2012. This will slow the growth in GHG emissions. By 2012, if progress has not been sufficient, and "sound science" justifies further action, the USA will respond with additional measures.

The Administration's plans emphasise voluntary partnerships to reduce emissions and develop technology, such as the FutureGen project where total spend has now reached $99M. Recent bills passing through the Senate Energy and Natural Resources Committee encourage improved energy efficiency and deployment of renewable sources of energy. One bill includes $125M for CCS research and development. Another bill will include provision to study the potential of CCS in the United States, reflecting legislation introduced by House Science and Technology Committee, to produce a comprehensive inventory of the nation's ability to store CO_2 in geologic formations and other natural basins.

The Office of Fossil Energy's Carbon Sequestration Program relies on private-public joint ventures in technology research, development and demonstration. The program is dedicated to developing multiple technologies for both pre- and post-combustion capture of CO_2 from the generation of electric power; and to developing technologies for the safe, long-term geologic storage of the greenhouse gas after its capture. More than $300M has been invested to date, although this figure presumably includes other forms of sequestration such as in forests, soils and the ocean.

7.4. Importance of government action

The importance of the government's role is well illustrated by a UK project proposed by BP, in partnership with Scottish and Southern Energy, in 2005. This was to be built at the site of the existing Peterhead power station. The project aimed to convert natural gas into hydrogen and CO_2 and use the H_2 as fuel for a new 350MW combined-cycle power station. The CO_2 would be piped to the offshore Miller field for increased oil recovery and, ultimately, storage. Detailed front-end engineering design work started in 2005. It was intended to make a final decision on investment in 2006 but this was delayed whilst the UK government considered the case for support. On the original schedule the project would have come into operation in 2010. Subsequently other companies also announced plans for CCS projects. Because these plants would be the first of a kind, they would be more expensive than later, commercial plants, so all of the developers indicated the need for some government help. The government commissioned an independent examination of the costs but the results have not been made public. In spring 2007, the UK government delayed a decision by announcing a competition for the first UK CCS project. Almost immediately, BP announced that it would not proceed with the Peterhead project because of the added delay in decision making and the uncertainty in timing. This illustrates very clearly the connection between current government policy and CCS project development. Many other projects in the UK and other countries have been announced with the caveat that they depend on government creating a suitable financial and regulatory framework.

7.5. International Cooperation

International cooperation on CCS comes in many and varied forms – a selection of the major initiatives is presented below.

International negotiations are now underway under the UNFCCC about emission-reduction objectives for the period after 2012. The European Commission would like to see geological storage of CO_2 recognised as part of the portfolio of options necessary for the implementation of such an agreement. It would also like to see CCS recognised under flexible mechanisms such as the CDM.

The European ZEPP TP, with representatives from all relevant industries and some ENGOs, is primarily a vehicle for influencing the European Commission about CCS but is also a means for Europe to build links for other countries such as China and India.

The EU has a formal partnership (called COACH) with China on demonstration of CCS. This will have 3 stages, starting with exploratory work, followed by the design of a demonstration project, then construction and operation. The first stage should be completed by end of 2008, with the operation of the demonstration project planned for 2015. A related cooperation (called NZEC) is underway between the UK and China; these 2 activities are coordinated with each other. The European Commission would also like to establish cooperative projects with other developing countries, such as India and South Africa, including development of appropriate policy and regulatory frameworks in those countries. The Commission will examine options for co-financing such projects and for coordination of demonstration projects in the EU and in third countries. The Commission also seeks to identify and exploit "synergies" with efforts under way in other coal-using economies (including the USA, Japan, Australia).

The USA has a number of bilateral science and technology agreements with other countries for information sharing and technical cooperation. These agreements also provide US scientists with opportunities to gain access to, and build upon, other nations' research. Current examples are:

- Cooperation with China: Annex IV includes a study of CO_2 Sequestration with Ammonium Carbonate and a proposal for a U.S.-China Carbon Capture and Sequestration Centre.
- Cooperation with Australia involving pooling of R&D efforts in Gasification and IGCC technology development, CO_2 sequestration, advanced combustion and synthetic liquid fuels
- Cooperation with Canada on the Weyburn monitoring project: Phase II of the project will create a Best Practice Manual, provide a comprehensive dataset for international comparison of CO_2 storage projects, and enhance the risk assessment model and process.
- Cooperation with Norway including carbon sequestration, hydrogen and clean fuels, and new energy technologies. Current projects include the Zero Emissions Norwegian Gas Project, the Advanced Non-Polluting Gas Generator, 70 MW Enhanced Oil Recovery Project and a Gravity Survey at the Sleipner project.

Australia is a leading player in the Asia-Pacific Economic Cooperation (APEC) which has already supported some work on establishing the capacity for storage in South-East Asia (APEC, 2005) and is planning further work on CCS. Australia and China have formed a Joint Coordination Group on Clean Coal Technologies.

Japan has extensive cooperation with neighbouring countries but not on CCS as far as is known.

The IEA Greenhouse Gas R&D Programme is the oldest international collaborative activity on CCS. It was established in 1991 and has members from many IEA and other countries as well as from the oil and electricity industries. It provides members with evaluations of technology and information on developments as well as promoting co-operation between specialists working in particular fields.

The Carbon Sequestration Leadership Forum (CSLF) is a voluntary initiative established and led by the USA. It brings together developed and developing nations for development of CCS technologies. It has 2 main areas of activity led by specific groups on technology and on policy. Activities include promoting the appropriate technical, political, and regulatory environments for the development of such technology. Current members are: Australia, Brazil, Canada, China, Colombia, Denmark, European Commission, France, Germany, Greece, India, Italy, Japan, Mexico, Netherlands, Norway, Russia, Saudi Arabia, South Africa, South Korea, United Kingdom, United States. 19 projects in member states are recognised by the CSLF. The CSLF was identified by the Gleneagles Plan of Action as a medium for cooperation and collaboration with key developing countries in dealing with greenhouse gas emissions.

The 2005 G-8 Summit adopted the Gleneagles Plan of Action on Climate Change, Clean Energy and Sustainable Development. Part of this included a commitment to accelerate the development and commercialization of CCS technology. Topics to be addressed included:

- barriers to the public acceptance of CCS technology;
- short-term opportunities for CCS in the fossil fuel sector, including EOR and CO_2 removal from natural gas;

- understanding of the concept of "capture ready" plant and consideration of economic incentives;
- collaboration with key developing countries on geological storage;
- exploration of the potential of CCS technologies with existing national programmes, industry and developing countries.

The World Bank is leading the G-8 initiative on a Clean Coal Technology investment framework, including support for low carbon technology (also see chapter 9).

8. Trends in CCS

From the information collected in this survey, it has been possible to identify a number of trends in the development and application of CCS. In this chapter the overall shape and pattern of development of the CCS technologies will be summarised.

Capturing, transporting and storing CO_2 adds cost to the process of power generation - there is no evidence that this additional cost can be avoided but there continues to be hope that it can be reduced. Already it has been seen that, by giving attention to this, established suppliers have been able to reduce the cost of capture – the CO_2 Capture Project aimed to reduce the cost of capture below US$30/t, which was said to be half the previous value; European funded projects under the 6th Framework Programme aimed to reduce the cost of capture to €20/t and 7th Framework projects are aiming to cut this further to €15/t. However, there is no clear explanation for the specific targets adopted. It seems to be expected that large scale application of CCS can be done at costs around the level that CO_2 is expected to trade at the start of the second phase of the ETS.

Such costs will be achieved only in multiple applications of the technology, and certainly not in the first plants to be built. There is confidence that *experience rates*[7] seen in related technologies (such as FGD) will also be found in the application of CCS. However, few projects will proceed in the near future without support from public funds as the costs of these first plants will be considerably higher even than the costs projected for CCS in large-scale use; for example, the 3 lead projects in the UK are reported to be asking for support of US \$600M each; FutureGen is expected to receive a similar level of support from DOE. There are a number of reasons for this – one-off costs because of lack of established infrastructure and lack of experience of the contractors, coupled with the lack of economies of scale in manufacture and especially for transportation where the cost of pipelining CO_2 from a single power station can be as expensive as the capture equipment. As more plants are built for commercial reasons, these additional costs can be expected to diminish.

The most significant development in transport would be if large pipeline networks were to be developed to handle CO_2 from more than one source. There may be legal reasons why this will not happen immediately, certainly for storage offshore, but eventually this will offer another means of reducing cost.

In many places, including Europe, USA and Australia, conventional coal-fired power plants have been ordered which will qualify for *grandfathering* when restrictions are imposed on CO_2 emissions. The European Commission has recognised this issue but has done nothing about it yet. Grandfathering will reduce the opportunity for building new plant with CCS. Associated with this is the trend of power plants being described as 'capture-ready'. It can be predicted with confidence that this trend will continue since, at present, the substance of the claim is not subject to strict scrutiny, except perhaps by some ENGOs such as in Australia.

Other sources of CO_2 from fossil fuel combustion, even though they may offer lower cost opportunities for capture, still do not attract much interest for use of CCS. There could be many

[7] i.e. the rate at which the cost of a technology reduces with expansion of its installed base.

reasons for this including lack of regulatory attention and poor financial performance of some of the industries concerned. The exception is CO_2 separated from natural gas – this is the source of CO_2 which has been used since practical CCS projects first began. Several further projects are expected to come on stream in the near future – this is likely to be a continuining trend, especially as new natural gas fields in several parts of the world seem to have higher CO_2 levels than older ones.

In terms of capture technology, post-combustion capture is most suitable for fitting to the existing designs of power stations (PF, NGCC) although there is concern about the energy requirements and cost. Solvent scrubbing remains the most established technique for separating CO_2; the challenge of CO_2 capture has shown that the licensors can improve the technology; further improvement can be expected because of the competitive nature of this business. Novel solvents have been announced and it is likely that further are in development. Because this technology is commercially available and there is a wealth of associated experience, it is expected that this will continue to play a major part in CCS. It is also relevant for other applications such as blast furnaces, in iron manufacture, and oil refineries.

Pre-combustion capture involves modest change to the design of IGCCs so application depends on wider acceptance of IGCC. There are signs of this happening in Europe, Australia, Japan and the USA as well as in countries such as China which have developed their own IGCC. It may be that the need to capture CO_2 could be the long-awaited development which makes IGCC competitive with PF for new power plants. However, there are more proposals for building 'capture-ready' supercritical boiler plants than IGCCs. Similar technology could be applied in production of liquid fuels from coal or gas – as yet there are no practical proposals for this application of CCS but that may follow as restrictions on CO_2 become stricter whilst concern about energy security continues.

Following on behind these 2 capture techniques, oxyfuel capture still needs to be demonstrated in pilot plants but several such projects are now under development so rapid progress is expected in understanding the practical potential of oxyfuel techniques. The safest strategy is to move from laboratory studies to pilot plants of 10-30 MW capacity before engaging in full scale power plants – this is the approach adopted in several parts of the world An exception is SaskPower's proposed plant which, if it goes ahead, would represent a technological leap straight from laboratory to commercial-scale plant. Although one developer has targeted use of oxyfuel with natural gas, it is likely that the main application will continue to be with solid fuel. A possible application in cement manufacture has yet to be tested.

Other separation processes may eventually take over from solvent scrubbing but so far none has shown improvement over solvents.   A number of novel processes are being tested so perhaps one of them may provide significant cost-effective improvement. The use of chemical looping combustion with natural gas fired power plants seems potentially interesting. On the other hand pre-combustion decarbonisation of natural gas seems less attractive than was once thought to be the case.

Interest in geological storage of CO_2 tends to be distracted by the concept of EOR, in countries with appropriate oil resources. There continues to be misunderstandings about the usefulness of such techniques each in their own way – for example, the extent to which EOR guarantees complete storage has recently been questioned in the USA. No offshore EOR has been undertaken anywhere in the world although projects have been proposed in UK and Norway. There is still considerable uncertainty about this application, not least because of the high cost of retrofitting existing production platforms as was demonstrated by BP's decisions to pull out of, first, Forties and then Miller. Due to the generally higher cost of operations offshore, the price that operators would be prepared to pay for CO_2 is likely to be less than that seen onshore. For this reason and because of the greater well spacing offshore, the return on investment in offshore EOR is likely to be less than for onshore projects which will limit the commercial interest. Once the storage of CO_2 has commercial value, alternative field management techniques which maximise CO_2 storage (rather than minimise cost for oil production) are likely to be deployed.

Interest in use of CO_2 for enhanced gas recovery, especially in the early years of the life of a gas field, has attracted attention which is likely to expand providing there is positive feedback from the initial projects. Some commentators seem to expect EGR to be useful late in the life of gas fields but the potential for contaminating the gas with CO_2 will surely be highest at that point so the attractions are more doubtful.

Although use of CO_2 to enhance CBM production may continue in suitable coal-beds, the problems presented by low permeability coal-measures and the limited success in pilot studies in Europe will restrict the use of this technique. Sterilising coal measures (as a result of storing CO_2) in a country such as China (which is heavily dependent on this fuel) seems likely to meet resistance. Further work on the physical changes in coal as a result of absorbing CO_2 is expected to provide better understanding of the potential of this technique.

Even though depleted gas fields may be the most suitable places to store CO_2, most of the current and forthcoming storage projects will continue to use deep saline aquifers.

Estimates of the capacity for storage are being improved in individual countries (UK, USA, Denmark, Germany, China) and regionally (Europe, Asia). As potential sites are identified, more detailed investigations will be required, especially of relatively uncharted aquifers. Regions not yet covered by such surveys will need to be addressed.

Although oil companies were involved in all of the first storage projects, there are now signs that other companies are starting to become involved in transmission and storage of CO_2. Oil industry service companies are starting to take an interest in CO_2 storage, forming business units to take on storage projects, or offering verification services.

Monitoring of stored CO_2 is required for 2 purposes – management of the reservoir and verification (for regulators and financiers) of the retention of CO_2 in the formation. Further development of techniques will improve sensitivity of measurement. The philosophy of verification will dictate the measurements needed – whether this is to verify the amount in store (which will be more difficult to do as time passes and the CO_2 disperses) or to detect any leakage; this may be at the surface (which relies on finding likely leakage paths) or sub-surface (where the background flux does not interfere with the measurement).

Acceptance of the potential security of the storage has enabled rapid progress in the London Convention and OSPAR but the same understanding has not yet informed discussions in relation to the CDM. Although it seems likely that, within 18 months, the temporary obstacles presented by the EB's response will have been overcome, the detailed nature of the questions raised will present more problems for convincing the decision makers. In a related way, implementation of IPCC's 2006 Guidelines is likely to cast fresh light on the extent to which EOR projects are able to retain CO_2 which is likely to reduce the attractions of this type of project for CO_2 storage.

At the same time, confidence in CCS as a means of reducing emissions and its recognition under the European ETS will facilitate financing of projects in Europe and could be extended to other countries. The major obstacle, namely the forward-view on CO_2 allowances, will likely be overcome as equipment suppliers and end-users put pressure on the authorities to extend the scheme. However, the competitive situation, especially with respect to further use of nuclear power, is also likely to be affected by such developments.

In common with most energy technologies in many developed countries, the need for trained people to develop and implement CCS is likely to impose a constraint on application as the scale of use expands. The development of a cadre of skilled technologists and suppliers in countries such as China could provide part of the answer to this problem.

As yet public attitudes towards CCS are affecting decision makers, not least because of the lack of general understanding of the technology in many countries, not to say lack of interest. Deliberate programmes of public information by governments and industry will help to plug the gap but it seems likely that most interest will develop in places where pipelines will be installed, and close to storage locations onshore. Nevertheless, experience with the response to the CO2SINK project at Ketzin has indicated that, in the right circumstances, there can be positive local support. It has to be hoped that similar attitudes are experienced in other places

Development of suitable laws and regulations are likely to influence public attitudes, at least to the extent of demonstrating that government is taking a responsible approach to the new concept. Whether government is a promoter of the technology, or a regulator protecting public and national interest, will influence how the public sees the government's position. Reconciling these positions will need deliberate action.

Regulation of CCS plant should build on similar regulations developed for similar purposes, such as natural gas storage, and on experience elsewhere, especially codes of practice. In view of the willingness of individual countries to accept the experience of others will determine how easily such regulations can be developed. Procedures for permitting storage sites and pipelines will be based on existing procedures for oil and gas, where appropriate.

Liability will clearly be the responsibility of the operator during capture, transportation and injection for storage but responsibility for long-term management of the storage facility will be transferred to government at some point after injection has finished and the site closed. The Australian experience with developing an agreement for handling the transfer of liability may set an example to the rest of the world.

9. Advancing the deployment of CCS

In order to identify steps which could be taken to advance the deployment of CCS technology, it will be necessary to consider the factors which will influence the various stakeholders, either in the sense of encouraging application of CCS or overcoming obstacles to use of the technology. These are discussed first; recommendations for action are identified throughout this chapter.

9.1. Stakeholder requirements for deployment of CCS

Future application of CCS will depend on various factors – in the widest sense, there has to be acceptance of the need for reducing greenhouse gas emissions, with governments setting specific goals, such as a cap on emissions which is lowered with time. Unless all stakeholders believe that government intends to lower the cap progressively towards some understood future emissions target, they are unlikely to make the commitment necessary to build CCS projects, especially in power generation. Equally it will be important that governments apply caps on emissions from all energy intensive sectors; this will encourage some of the lower cost applications of CCS in energy-intensive industries, such as iron, chemicals and cement manufacture. Once the level of the cap is low enough, the price of emission allowances[8] will rise to such a level as to justify use of CCS but investment will not happen on any scale until allowances are available for a sufficient number of years ahead.

The prospective owners of CCS plants will need to have confidence in the technology, not only that it can reduce emissions and there is a means of paying for it but, more important, that the plant will deliver a reliable service for a long life without exceptional maintenance requirements (as well as meeting all of the operational requirements of conventional power plant). The owners will also need to know that there are adequate geological reservoirs available for use at reasonable cost in nearby locations, and that any potential conflict with other users of the sub-surface (such as for oil production or for natural gas storage) can be resolved.

[8] Although this is described in terms of emissions trading, developments in other financing systems would have a similar effect.

There seems to be growing confidence amongst equipment suppliers that CCS will be part of the future of their industry but whether there are suppliers of geological storage ready to offer such services is less clear. Without this, responsibility will fall on the user to arrange for storage but few of them (e.g. electricity companies) have any geological expertise which would give them confidence in this stage of the process. More consideration should be given by industry, governments and international bodies as to how this part of the CO_2 chain will be supplied.

Both the equipment suppliers and their customers will expect to work to technical standards for designing and operating CCS plant. They will also expect that regulators would be able to approve their plans, such as for the design and operation of pipelines especially where these pass close to inhabited areas. Some stimulus to the development of standards is required.

Equally important will be the reliability of the storage facility, especially if onshore, to ensure that there is no threat to health or the environment. The regulators will look to see that risk assessments have been carried out and that the basis for them is fair and reasonable. At present there is very little practical data from CO_2 storage facilities so information from analogues will likely be used in models as the basis for risk assessment. Further risk assessments should be carried out and the results published to encourage scrutiny and understanding.

As with every part of the chain, storage of CO_2 will have to conform to the law but, in particular, the responsibility for liability must be clear, in case there were to be leakage (whether this might result in reduction of climate benefits or, more seriously, threaten safety). Long-term responsibility for the store after the end of injection will also have to be defined, so as to ensure that others do not drill into it at a later date, and to accept liability in case of accident. It is expected that responsibility for stored CO_2 will eventually be transferred to government so the precise circumstances of this handover have to be defined.

None of this will be of any merit if there is strong reaction against the technology from the public. In order for there to be widespread application of CCS, there will need to be, first, public education on climate change and the options for mitigation, amongst which CCS can be made known. Deliberate engagement of the public in considering the merits of CCS will be an important aspect of successfully gaining support for the future use of CCS.

9.2. Potential for international cooperation

All of the above is based on domestic application of CCS. There will also be opportunities for global cooperation particularly between Annex 1 and developing countries. The nature of this cooperation will depend on the international agreements then in force, and the mechanisms for remunerating the investments that these provide. Without any foresight about the international agreement that will be in operation post-2012, the following discussion presumes a continuation of the Kyoto Protocol's mechanisms.

9.2.1. Storage capacity in developing countries

Although fossil fuels are extensively used in developing countries, it is the geology of the different countries that will determine whether storage of CO_2 is likely to be feasible. The most straightforward opportunity would be to store CO_2 in disused oil or gas fields or use it for EOR. The presence of such reservoirs may indicate suitable cap-rocks; depending on their geographical distribution, these might also provide the means to retain CO_2 in deep saline aquifers but generally these have not been explored. However, only some countries have oil and gas resources. So a lack of geological information presents a substantial obstacle to wider use of CCS – this is an important target for action.

Available information on oil and gas fields can be used to make an estimate, to 1st approximation, of the potential storage capacity in some of these countries. The capacity of these fields (once depleted) can be estimated from the amount of oil and gas produced to date plus that which is likely to be produced in future based on the current proven reserves (this method of estimating capacity is based on that used in APEC, 2005). This provides a figure for the technical (ultimate) potential for storage; it is likely that the practical capacity will be less than this but, without more detailed information on the sub-surface, it is not possible to be more specific. Some estimates are shown in Table 9.1 for the main developing economies in Asia, as well as other oil producing countries in the region, and oil producing countries in South and Central America. The main OPEC countries (e.g. Saudi Arabia, Iran, Iraq) are likely to have great potential for storage.

Once the storage capacity has been estimated, a rough view can taken of the potential for capturing CO_2, to see how relevant CCS might be to the host country. Some idea of the sufficiency of the storage capacity can be found by comparing this with the level of national emissions, although that will tend to overestimate the amount of CO_2 which could be captured because it does not distinguish between small and large sources (Table 9.1).

Table 9.1 Theoretical storage capacity in oil and gas fields in certain developing countries

	Oil and gas field capacity (Gt CO_2)	National emissions (Mt CO_2/y) 2003	Capacity relative to emissions (years)
Argentina	4.8	127	38
Brazil	3.9	351	11
China	14.7	3960	4
Colombia	1.6	55	29
Ecuador and Peru	2.4	48	50
India	6	1066	6
Indonesia	14.8	318	46
Malaysia	10.3	141	73
Mexico	10	380	26
Thailand[9]	1.9	200	10
Trinidad & Tobago	2.7	30	90

These data only provide rough indications of potential capacity – they show that some of the largest developing economies have only relatively small storage capacity compared with total national emissions. It may be that deep saline aquifers would also be available in these countries – this is not known at present but is something which should be investigated. Without suitable reservoirs, if these

[9] The APEC study (2005) notes that some of the hydrocarbon bearing formations in Thailand may be problematic for storing CO_2 due to their discontinuous nature.

countries eventually accept targets for emission reduction, much of the mitigation effort would have to be provided by means other than CCS.

In some countries, such as Indonesia and Brazil, the distances are great between most of the current sources of emissions and some of the potential storage locations. The distance between sources and possible stores needs to be investigated, to confirm what fraction of national emissions could be addressed by CCS.

Argentina, Mexico and several other countries have relatively low reserves of oil and gas at current production rates which suggests that, as well as substantial opportunities for storage in depleted oil or gas fields, there may well be considerable interest in use of CO_2 for EOR. This may give greater motivation for the nation concerned to consider capturing CO_2 and could be used as the basis for a campaign to broaden interest in CCS in South/Central America.

9.2.2. CDM

It will be the host's decision whether a CDM project activity assists it in achieving sustainable development. The proponents of a CCS project should be able to demonstrate that the technology and know-how to be transferred are sound and environmentally safe. Some developing countries and ENGOs are concerned that CCS might "crowd out" other CDM projects – this concern is unlikely to disappear. So work is needed to develop a more sophisticated (and hopefully more balanced) view. Unless this happens, the potential for CCS to be applied in developing countries will be limited.

Another necessary condition for such projects is that the UN's CMP.4 meeting in late 2008 accepts CCS as suitable for CDM projects without significant additional constraints. This will require that decision makers in the UNFCCC receive sufficient and convincing information on CCS to address the issues that were raised at CMP.2. The difficulty with this is that answers to some of these questions rely on expert judgement based on current understanding of geological storage (e.g. the level of leakage likely from CO_2 stores). There would be merit in trying to assess the level of understanding of the SBSTA before this information is formally discussed in order to develop appropriate means of briefing the participants.

Some of the issues raised at CMP.2 are not covered by IPCC's 2006 Guidelines, especially those concerning management of the storage facility. This will require development of international standards for management of CCS facilities.

9.2.3. JI

Use of JI to support CCS projects in other Annex 1 countries would superficially seem to have attractions. Some of the countries which have recently joined the EU have extensive, old oil and gas fields which might be suitable places for storage. However, it is not obvious that CCS would be substantially less expensive in one Annex 1 country than in another, which may be the reason that little consideration seems to have been given to using JI to support CCS projects. If JI could be used in developing countries, this might suit some sponsors but, as it would require the host countries to accept limits on their emissions, it seems unlikely that this will happen soon. No action is proposed in respect of CCS under JI.

9.2.4. Other international funding

The World Bank and the Asian Development Bank are promoting use of state-of-the-art power generation technology. For example, the World Bank has assisted China in its expansion of coal-fired power generation. In particular it has helped improve environmental performance through introduction of new large-scale supercritical and ultra-supercritical units with increased efficiency, as well as advising on methods of implementing FGD and rehabilitation of medium size power plants to improve efficiency with retrofit of environmental control systems.

The World Bank is supporting the Chinese government in the demonstration of IGCC, including examining ways of reducing the capital cost. It is also helping the government to develop a long-term strategy for "zero-CO_2 emissions from coal". In particular, it has offered to meet part of the incremental cost of making design changes and increasing the capacity of the IGCC plant for this purpose, to test various types of Chinese coal, and equip the plant for future use of CO_2 capture and storage, and hydrogen production. The World Bank funded a study for the State Grid Xinyuan Corporation in 2006 examining options for including CCS in an IGCC to be built at Yantai in Shandong province. It would seem likely that further activity in relation to CCS will be supported by the World Bank, although, as yet, the GEF does not seem to provide much investment for large, fossil-fuelled power projects even using CCS. Nevertheless, given that other supra-national bodies (such as the European Commission) have been persuaded to change their collective mind about CCS, it is proposed that action should be taken to encourage the GEF to support CCS projects, and extend this to other suitable countries such as India.

Several national (e.g. USA) and supra-national (e.g. EC) bodies have bilateral agreements with countries such as China and India which could be vehicles for funding CCS projects; in some cases, these are already expected to lead to support of full-scale projects (e.g. the EC COACH project). Oil and gas companies are likely to undertake further CCS projects in association with natural gas production – the first example was the In Salah project in Algeria which is operated by BP; ExxonMobil's contract to develop the Natuna-D project, offshore Indonesia, was brought into question in 2006 because of the cost of the CCS component, even though many years had been spent trying to find an acceptable path for development. Another CCS project has been proposed in Malaysia for injecting CO_2 extracted from a natural gas stream into a geological formation. Shell has also proposed using CO_2 captured onshore for EOR in the White Tiger oil field offshore Vietnam. It seems likely that these would be just the first of many if suitable finance were available for CCS projects in developing countries.

9.3. Challenges to the developer

As with any import, the developer of CCS technology will face challenges in supplying equipment to developing countries, such as China, not least in gaining permission to supply their equipment, as well as handling import taxes, providing a required level of local content whilst protecting IPR, and many other aspects. More specific to CCS, the developer will have little in the way of demonstrated technology that can be cited as working examples because so few of them have been built to date.

Protecting IPR whilst attracting customers requires a delicate balance on the part of the developer. In China, for example, there is increasing interest in use of gasification of coal to supply power and to make liquid fuels; several projects will use imported gasifiers (Shell or GE) but home-designed gasifiers are now being developed and are expected to form the basis for the new generation of power plants. European and other funding is supporting Chinese institutions in learning about the potential for capturing CO_2 from both imported and home-developed gasifiers. The eventual benefit seems likely to accrue to the Chinese manufacturers. So international collaboration with developing countries must try to achieve the difficult goal of meeting the needs of the developers whilst building the capabilities of key manufacturers in the host countries.

The initial CO_2 capture projects in a particular area would likely transport CO_2 from a single source to a single storage location. However, such an approach would suffer relatively high specific costs for transport. The transport costs (per tonne) could be reduced by building larger pipelines to handle CO_2 from several sources but establishing such a network would require large initial investment. One solution would be to encourage government, or international funding bodies, to contribute to developing pipelines, as has happened in Norway.

Geological storage capacity figures will be subject to revision as more detailed surveys are carried out so initial estimates should be treated with some caution. Many of the possible storage sites being considered in Europe are under the sea but, in China, most of the sites considered are inland, where there may be problems in gaining permission for storage. Undersea storage would not be an option for most of the country due to the distance involved, amongst other things. Individual developers are unlikely to commit to area-wide investigations of storage capacity, so international funding might be the only way to establish the potential for storage, as is happening in parts of China under EC funding. International funding should be used to replicate this elsewhere.

Other applications of CO_2 capture, such as concentrated emissions of CO_2 available in ammonia manufacture, would be relatively inexpensive and so could be justified without the need to accept deep reductions in emissions; the same could apply to emissions from coal-to-liquids plants. These potential early opportunities for application of CCS should be addressed more aggressively.

In order to accelerate the speed at which a new industry becomes established in the market place, pump-priming from public funds will be necessary. Given the societal benefit of limiting GHG emissions whilst maintaining reliable energy supplies, a case can be made for public support. However this is a difficult balance to strike, especially to persuade large companies to innovate without encouraging them to be dependent on hand-outs from the public purse. As demonstrated in the case of the Peterhead project, sometimes the developer will just walk away if decisions are delayed too much.

In some developed countries, the supply of skilled staff is becoming a constraint on development of business. This is not a problem specific to CCS so there is little which can be added here to the general concern about this topic. Training technicians in countries such as China could be part of the answer.

9.4. Challenges to the host

To enable wide-spread application of a mitigation measure, especially one such as CCS which will involve large capital investment, a host country would have to accept targets for emission reduction. Accepting such a commitment will involve many more factors than just the ability to conduct CCS projects.

In Annex 1 countries, in order to justify use of CCS in power generation it will be necessary for the host country to accept the need for moving towards deep reductions (>80%) in emissions from power generation. This would be reflected in a lower cap on emissions which would also tend to raise the marginal price of CO_2 emission allowances.

In developing countries, before they have accepted emission reduction targets, CDM projects would provide a way to start building experience with CCS technology. Thus the forthcoming decision on the CDM will be key to early use of CCS in developing countries. This would be a form of national capacity-building. However, if these countries do eventually accept national emission reduction targets, it seems likely that the required reductions will be less severe than those accepted by developed countries (which have higher national emissions per capita and a longer history of GHG emissions). This will make it more difficult to justify CCS projects. So the initial capacity-building in CCS may be wasted unless there is some means for follow-on projects once the CDM funding is exhausted. This requires action to ensure ongoing support for CDM-like projects once the CDM funding ends.

In countries with large fossil fuel reserves, use of CCS offers a way to reduce emissions whilst maintaining national energy security. This seems likely to be of increasing importance with perceived threats to international supplies of oil and gas. For example, the Chinese Government is committed to a programme of power sector expansion largely based on coal but with environmental protection. The 11th Five-year Plan includes reference to:

- Focus on large, high efficiency power plants with environmental protection.
- Promoting electricity generation using clean coal technology.
- Start up of an IGCC project.
- Development of pithead power plants.
- Development of electricity generation using natural gas.

This plan included 6 potential IGCC projects, at various stages of development. This reflects an intention of the Chinese government to bring down costs by ordering multiple units. The Chinese attitude is broadly similar to that of other countries. At present, PF technology is preferred for power generation as it has lower capital cost and greater reliability and availability than IGCC, within the current environmental/regulatory frameworks. However, environmental regulations are becoming stricter. IGCC can already remove almost all pollutants while PF plant will need additional investment in order to remove further pollutants. This will change the relative costs of the 2 technologies as emission standards become tighter. When CO_2 capture is considered, IGCC becomes more attractive still; IGCC is also the technology of choice when the production of hydrogen from coal is considered. In today's perspective, both IGCC and PF have merit for reducing CO_2 emissions and so it is sensible for China and other countries to include both options in their plans. In terms of use of CCS, both of these technologies are "near-commercial", and are dependant on large-scale demonstration to make significant progress towards wide-scale application. As the World Bank has done, international funding should be used to promote such demonstrations.

Other countries, without access to power generation from their own fossil fuels reserves, may turn to nuclear power as a reliable, low GHG emission source of electricity, as has been the case in Iran and North Korea recently. This can raise concerns elsewhere about the dangers of recycling nuclear material and consequent proliferation of nuclear weapons. By providing a route to generate electricity from fossil fuels, CCS avoids this particular source of international tension.

In any country there will be environmental protection and some form of regulation of what is done in exploiting the sub-surface. In China mapping of potential CO_2 storage sites is now starting with support from the EU and Australia. However, alongside such studies, it is also important to consider the need for regulations and standards as well as proven methods of monitoring and verification. Especially in countries new to CCS, the regulators will need to know enough about the technology to consider projects for approval. So a particular challenge for developing countries is how much effort to put into developing appropriate safeguards. If they recognise the need for a strong regulatory framework to minimize the risks and liability to future generations and the environment, this may take some time to develop which could delay projects. Without it there could be concerns lest the projects compromise sustainable development.

Even in developed countries there has been only limited investigation of what the public thinks about CCS. The attitudes of ENGOs in these countries are changing towards CCS and this could influence public attitudes. Whether there is need for proactive work by extending surveys of public attitudes to other key countries is open to question. Remembering what has been learnt in developed countries, there has to be understanding of climate change and mitigation options in general before CCS can be put in a proper context. Nevertheless, anyone living near CO_2 pipelines or storage sites might feel concerned about what was being done, so there will be a need for public information campaigns as part of the development of CCS projects. It would be worthwhile sharing experience of communication strategies.

9.5. Conclusion – potential for deployment

Developing and implementing low emission electricity generation technology is handicapped by many factors, not least the relatively low rate of return implicit in any such utility investment. This limits the motivation to take bold steps. Recognising the long-term public good of deploying CCS technologies, governments will have to develop policies which incorporate some positive inducements and some penalties in order to achieve suitable progress. In terms of application in developing countries, many of these problems seem to be enlarged so the timescale for application is likely to be longer than in developed countries. Nevertheless it is important to engage developing countries in these projects, recognising that the extended timescales for the early projects will not present a problem because, until these countries accept targets for emission reduction, there will be little opportunity for expanding application of CCS beyond a few initial examples.

10. Conclusion

In a field as new and wide ranging as CCS, there will be many ideas for actions that should be taken to accelerate the deployment of the technology. The following are offered as suggestions of some of the most important items, in the author's view. There is great scope for discussion and debate.

10.1. Recommendations

Recommendations about possible ways to move CCS forward include identification of possible policy options and other measures that could contribute towards enhancing deployment and transfer of CCS technologies, taking into account the interest of both the developer and the potential user.

10.1.1. Technology

1) Encourage novel ideas to reduce cost of CO_2 capture but recognising that existing technology presents stiff competition since it is also open to improvement.
2) Support geological investigations in potential host countries to delineate, especially, the potential for storage in deep saline aquifers.
3) Map the position of future sources (of all types) and potential storage sites to investigate feasibility.
4) Develop international standards for design and management of CCS facilities. This will be relevant not just to the needs of project developers but also provide an indication, to regulators, of the quality of the projects and, to the public, that there are recognised approaches for deploying CCS.

10.1.2. Finance

5) Encourage the CDM EB to support the use of CCS in developing countries.

6) Investigate potential for other funding bodies, such as GEF, World Bank, and Asian Development Bank, to support CCS projects.

7) Extend European ETS in perpetuity. Substantially lower the cap in phase 3 (post-2012).

8) Encourage other countries to establish their own emission trading schemes and link them to ETS.

9) Encourage commercial sources of finance to take part in CCS activities e.g. European Investment Bank and others.

10.1.3. Health, Safety and Environmental Regulation

10) Assemble data to substantiate the claims of low leakage from storage facilities by further, monitored large-scale injection projects – ideally several in each region and with a variety of geological formations.

11) Promulgate understanding of the results of as many risk assessments as possible, to build confidence.

12) Encourage national development of suitable regulatory frameworks for CCS, taking account of experience elsewhere.

10.1.4. Public attitudes

13) Improve public understanding of CCS as this could be a critical factor in determining the success of plans for large-scale deployment. Recognise that the timing of any public information campaign has to be coordinated with the need for awareness and a recognised wish by the public for information, otherwise it could be wasted or even counter-productive. Carry-out regular surveys of public attitudes in any country that is likely to want to use CCS, in order to calibrate changes in attitude.

10.1.5. Policy

14) Adopt policies for reducing greenhouse gas emissions which lead to stabilisation of the atmospheric concentration of CO_2 before the end of the 21^{st} century.

15) Assess the level of understanding of the SBSTA about CCS before it is formally discussed and develop suitable, detailed briefings for that Body.

16) Encourage GEF to accept CCS as possible low-emitting technology suitable for future action.

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