UNITED
NATIONS

E

Economic and Social Council

Distr.
GENERAL

ECE/ENERGY/2006/5
18 September 2006

Original: ENGLISH

ECONOMIC COMMISSION FOR EUROPE

COMMITTEE ON SUSTAINABLE ENERGY

Fifteenth session
Geneva, 28 – 30 November 2006
Item 8 of the provisional agenda

OVERVIEW OF CARBON CAPTURE AND STORAGE TECHNOLOGIES, OPPORTUNITIES, BARRIERS, ECONOMICS AND RECOMMENDED ROLES FOR THE UNECE

Note by the secretariat*

I. INTRODUCTION

1. There is increasing concern about climate change, which is believed to be occurring due to a rise in the concentration of greenhouse gases (GHGs) in the atmosphere.

2. Carbon dioxide (CO_2) is the main GHG arising from human activities. The main source of CO_2 emissions is fossil fuel combustion, although destruction of tropical rain forests is also responsible for a significant amount of these emissions. Power generation is the single largest sectoral contributor of anthropogenic CO_2 emissions on a global basis, so it tends to attract much attention in terms of reducing emissions.

3. There are a variety of options available to reduce GHG emissions, including increasing the efficiency of using energy, switching to lower-carbon fuels, or substituting electricity from alternative sources such as renewable energy or nuclear power. Efforts are underway to implement such measures in the UNECE region and elsewhere around the world. Until recently

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it was tacitly assumed that reducing GHG emissions also implied moving away from using fossil fuels, but many policymakers now consider this to be unfeasible given the significant economic growth in developing countries and transition economies and the growing emphasis on energy security. Significant effort in research and development, however, is leading to ways of using fossil fuels, especially for power generation, with much less emissions than in current plants. This can be achieved by capturing and storing the CO_2, which is the subject of this paper.

4. CO_2 capture and storage (also referred to as carbon capture and storage or CCS) is based on technology already in use for other purposes, so there is limited need for development; this relative maturity also gives greater confidence in its application compared with other novel energy technologies at a similar stage in their development. Thus it is a technology that could be deployed relatively rapidly to reduce GHG emissions from fossil fuel-fired plants. The main examples in this paper are drawn from power generation, but similar remarks could be made about application in other large, central plant using fossil fuels, such as oil refineries, iron and steel works and hydrogen manufacture.

5. In this paper, the technology for capture and storage of CO_2 is introduced first, including an outline of the costs and potential capacity for reducing emissions. The reasons for the current interest in this approach are then considered, including a brief examination of various, other ways of reducing GHG emissions. Barriers to implementation are then discussed and the work necessary to overcome them considered. Institutional needs specifically associated with this technology are reviewed, ending with an examination of some international collaborations. Finally, some possible roles are suggested for action by UNECE in this area.

6. The purpose of this paper is to provide the Committee on Sustainable Energy and the Ad Hoc Group of Experts on Coal in Sustainable Development with an introduction to CO_2 capture and storage. There is significant potential for these technologies in the UNECE region, and the paper will serve as the basis for further discussion on the role of the UNECE in supporting member States' interests in this subject.

II. WHAT IS CO_2 CAPTURE AND STORAGE?

7. There are three main elements to the process - namely capture, transportation and storage of CO_2 (see figure.1). These will be introduced separately before proceeding to a discussion of the system and its application.

(a) CO_2 Capture

8. First, the CO_2 must be separated from the flue gas or some other gas stream. The nature of the gas stream depends on the type of power plant: in a conventional coal-fired power plant burning pulverized fuel (PF), the flue gas stream is mainly nitrogen, so the capture process has to separate CO_2 from nitrogen in an oxidizing atmosphere. In this case, capture is undertaken at the end of the process, so this is referred to as post-combustion capture. This approach could also be used with gas-fired plant.

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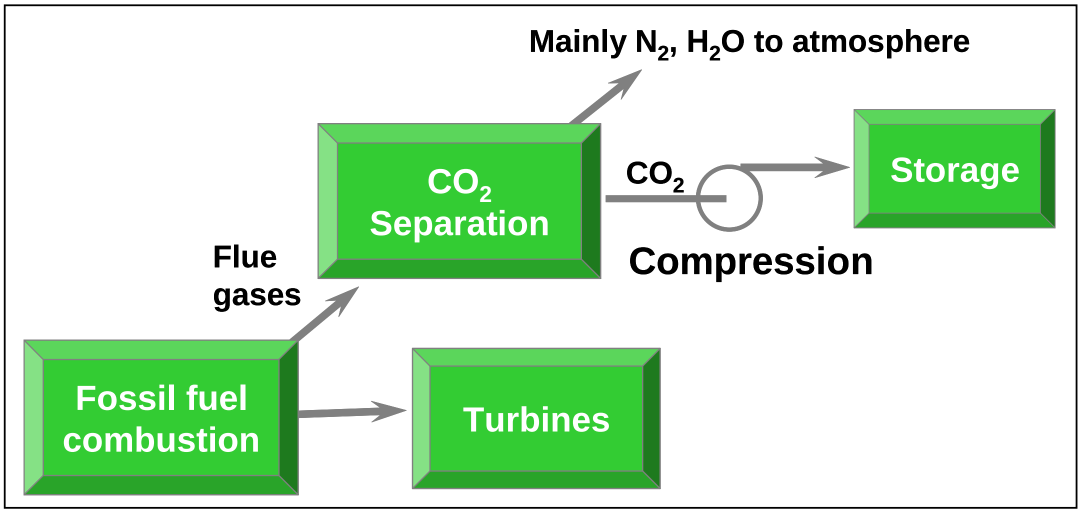
Figure 1: Schematic Diagram of CO_2 Capture and Storage



10. Another option, the integrated gasification combined cycle (IGCC) plant, would provide a hydrogen-rich atmosphere for separation. This is termed pre-combustion capture, as the separation is carried out in the fuel gas prior to combustion. A related process can be used with natural gas. A third option, called oxyfuel combustion, involves separation of oxygen from air before it is supplied to the combustion chamber. This avoids introducing nitrogen into the combustion process, so simplifying the separation of CO_2.

11. There are at least four main techniques for the separation of CO_2; other approaches are under development:

(i) Scrub the flue gas with a re-usable chemical solvent, such as an amine, or a physical solvent, in a manner analogous to flue gas desulphurisation (FGD).
(ii) Adsorb CO_2 using a solid adsorbent – the adsorbent would be regenerated after use, by cycling temperature or pressure.
(iii) Separate CO_2 using a semi-permeable membrane, an established technology now being adapted for use with CO_2.
(iv) Cryogenically remove CO_2 – another established technology, best suited to gas streams having high concentrations of CO_2 (much higher than the 3-13% found in flue gases).

12. Flue gas scrubbing is already used in a few PF power plants to produce CO_2 for the food industry. After capturing the CO_2, the amine from the scrubber is heated to release high purity CO_2 so that the solvent can be reused. This technique is well established in other applications, such as separation of CO_2 from natural gas. The low concentration of CO_2 in power station flue gas means that a large volume of gas has to be handled, which results in large equipment sizes

and high capital costs. A further implication of the low CO_2 concentration is that powerful solvents are needed – the regeneration of which requires large amounts of energy.

13. If the CO_2 concentration and pressure can be increased, the capture equipment would be smaller and there would be lower energy penalties for regeneration of the solvent. This can be achieved using pre-combustion capture. In this case, the fuel is reacted with oxygen and/or steam to form a synthesis gas, consisting mainly of carbon monoxide (CO) and hydrogen (H_2). The CO is then reacted with steam in a catalytic shift converter to give CO_2 and more H_2 – the shift converter is proven in ammonia production and other chemical processes. The CO_2 is separated before combustion and the H_2 used as fuel in a gas turbine combined cycle. Although pre-combustion capture would involve a more radical change to power station design than post-combustion capture, most of the technology is already available.

14. In the oxyfuel approach, purified oxygen is used instead of air for combustion. Some CO_2-rich flue gas is recycled to the combustor to moderate the flame temperature, but the separation of CO_2 only requires simple CO_2 purification so virtually all the CO_2 is captured and emissions of CO_2 will be close to zero. The disadvantage of this approach is that production of oxygen is expensive, both in terms of capital cost and energy consumption.

(b) Transportation of CO_2

15. After the CO_2 has been captured, it is pressurised, reducing its volume substantially, and then transported to the storage site. This can be done using high pressure pipelines, or by ship. Again this is known and proven technology. The CO_2 would be pressurized to about 100 bar at the power plant, putting it into a dense state (the density is slightly less than that of liquid water). Compression accounts for about a quarter of the overall energy consumption and cost of the whole process.

(c) Storage of CO_2

16. There is a range of possible storage options for CO_2 including oil and gas reservoirs, deep saline aquifers, and unminable coal beds. Storage must ensure there is virtually no leakage. The permanence of CO_2 held in geological formations is indicated by the natural CO_2 fields that exist in several parts of the world; CO_2 has been stored in these fields for tens of thousands of years. If engineered stores can emulate the performance of these natural fields, then it should be possible to store CO_2 safely for as long as is necessary to protect the climate.

17. Natural reservoirs, such as depleted oil and gas fields, potentially have sufficient capacity to store many decades of emissions of anthropogenic CO_2. Oil and gas fields have a number of attractive features as CO_2 stores:

(i) Exploration costs would be small;
(ii) The reservoirs are proven traps for fluids, having held liquids and gases for millions of years;
(iii) Their geology has been thoroughly explored; and
(iv) The potential exists to re-use some of the production equipment to transport and inject the CO_2.

18. In most oil fields, only a portion of the original oil in place is recovered using standard extraction methods. CO_2 injected into suitable, depleted oil reservoirs can extract more oil - typically 10-15% more; this is a recognised technique for enhanced oil recovery (EOR). Much of the injected CO_2 would remain underground at the end of oil production. Sale of the additional oil produced could more than offset the cost of CO_2 injection. About 30 Mt/y of CO_2 is already used in 73 EOR projects in the United States (most of the CO_2 comes from natural sources).

19. Depleted natural gas fields are also feasible sites for CO_2 storage; some could easily be adapted for this purpose. Another type of underground reservoir suitable for CO_2 storage is a deep saline-water-filled aquifer. Injected CO_2 displaces water in the aquifer and partially dissolves. In some formations, CO_2 would slowly react with minerals to form carbonates, which would lock up the CO_2 essentially permanently. As with other storage formations, suitable aquifers must have a cap rock of low permeability to minimise CO_2 leakage. Also, there must be little or no prospect of them being used as a source of water. Injection of CO_2 into deep saline reservoirs would use techniques similar to those for disused oil and gas fields.

20. Underground storage in depleted gas fields and deep salt-water aquifers has been used by the natural gas industry for many decades for temporary storage of natural gas. This provides an important analogue for CO_2 storage – much can be learnt from the practices developed for underground storage of natural gas to achieve safe and secure storage of CO_2.

21. Unminable coal beds could also be used to store CO_2, by adsorption onto the coal. This process could lock-up CO_2 permanently, provided the coal is never mined as that would then release the CO_2 to the atmosphere. Coal naturally contains some methane, but it can adsorb about twice as much CO_2 by volume as methane; in the process of CO_2 adsorption, coal bed methane may be displaced, thereby providing a product for sale.

22. The global capacity for storage of CO_2 in geological formations has been estimated by various authors. Depleted oil and gas fields could hold up to 800 Gt CO_2 at a cost for transport and storage of no more than \$17/tCO_2; there is uncertainty about the capacity of deep saline reservoirs because very few have been surveyed for this purpose – the range of estimates is 1,000 to 100,00 Gt CO_2 worldwide at costs similar to storage in gas fields. Unminable coal measures could hold 15 Gt CO_2 worldwide at zero net cost, after allowing for the income generated by the coal-bed methane recovered. The storage capacity available within a reasonable distance of major sources of CO_2 will determine how much might be used in practice. This is now being investigated in various parts of the world.

(d) Other methods of storing CO_2

23. Deep ocean injection of CO_2 has also been the subject of considerable study. The oceans already contain large quantities of CO_2, but there remains substantial storage capacity. Among technically feasible options, however, ocean storage is very controversial due to the potential environmental impact.

24. Many other possible ways of storing CO_2 have been suggested, such as converting CO_2 into solid form, converting it into carbonate mineral, or even rejecting carbon rather than CO_2

from the process – none of these are economically competitive with the use of natural reservoirs, or have sufficient capacity, but some have the attraction of storing the CO_2 permanently as a solid.

25. Due to the large capacity, relatively low-cost and very limited environmental impact, geological formations are attracting most interest at present as a means of storing CO_2. The remainder of this paper will concentrate on this type of storage.

III. EMISSIONS REDUCTION

26. There are several factors to consider when estimating the emission reduction potential of CCS technologies. Most importantly, the generating efficiency and output of a plant are reduced because of the extra energy used by the separation equipment as well as the energy needed for compression of the CO_2. Other pollutants, such as SO_x and NO_x, must be removed from the gas stream before it reaches the CO_2 capture stage, so the total emissions of criteria pollutants from a plant fitted with CO_2 capture will most likely be less than from a plant without capture. The CO_2 emissions and efficiency of power plants incorporating CO_2 capture are shown in Table 1.

Table 1: Effect of Capture on Power Plant Efficiency and Emissions (500MW$_e$ output in each case)

Process	**Efficiency % (LHV)**	**CO_2 emission (g/kWh)**	**CO_2 emission reduction**
Supercritical PF with FGD (no CO_2 capture)	46	722	Reference
Supercritical PF with FGD and CO_2 capture[a]	33	148	80%
IGCC (no CO_2 capture)	46	710	Reference
IGCC with CO_2 capture[b]	38	134	81%
O_2 /CO_2-recycle combustion (IGCC)[c]	37	28	96%
Natural gas combined cycle (no CO_2 capture)	56	370	Reference
Natural gas combined cycle with CO_2 captured[c]	47	61	84%

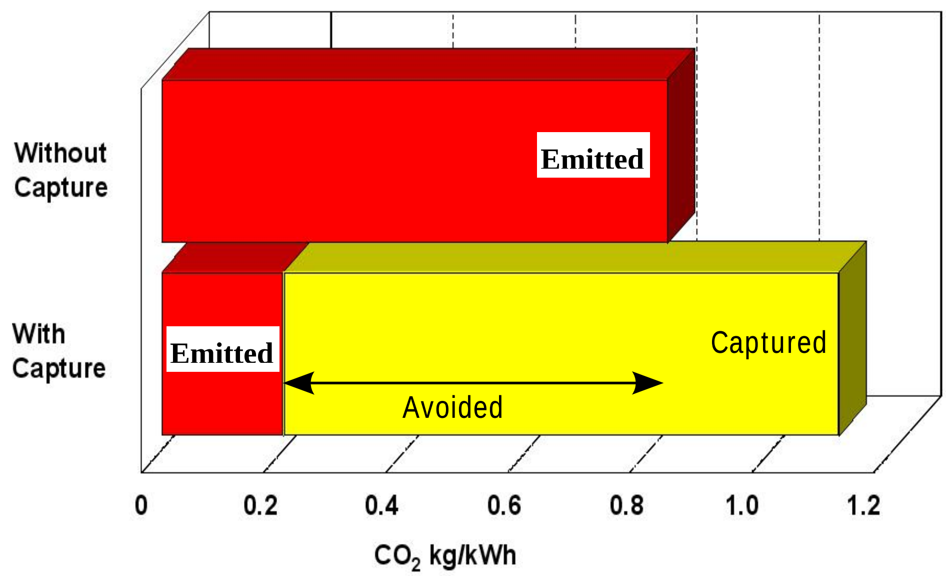
[a] Capture by amine solvent scrubbing,
[b] Capture is by physical solvent scrubbing
[c] In the O_2 /CO_2-recycle case, the CO_2 capture is essentially by condensation of water.

27. The efficiency penalty for CO_2 capture is lower in the IGCC plant than in the pulverised fuel (PF) plant, because the process operates at elevated pressure and less energy is needed for solvent regeneration. Emission reduction of at least 80% is achievable depending on plant type; the precise degree of reduction in these results is based on engineering judgment as to the optimum level. The O_2 /CO_2-recycle case assumes a gas turbine which uses CO_2 as working fluid – such machines do not exist at present. A simpler form of O_2/CO_2-recycle could be fitted to boiler plant but the efficiency would be low (about 33%) and emission reduction around 90%. In the natural gas case, the efficiency penalty is less than in the coal (PF) case, partly because the plant is more efficient than coal plant and partly because there is more hydrogen/less carbon in the fuel.

IV. COST OF CO_2 CAPTURE AND STORAGE

28. The published costs of capture and storage are a frequent cause of confusion because of the different base assumptions used for calculating cost. Amongst other things, costings must take account of the fact that emissions from such a plant are lower than those from a plant without capture but not by as much as the amount of CO_2 captured. This is because extra energy is used for capturing and compressing the CO_2, which generates extra CO_2. A key measure of the effectiveness of CCS is the amount of CO_2 emissions-avoided, which takes account of the extra energy used (see figure 2).

Figure 2: Emissions from Coal-fired Power Plants with and without CO_2 Capture



29. Cost per tonne of CO_2-avoided is often used as a measure of the cost of CCS. However, as a means of comparing mitigation options, cost/tCO_2-avoided can be confusing since the answer depends on the base-case chosen for the comparison (i.e. what is being avoided) – often, for convenience, the plant with capture is compared with the same type of plant without capture. However, this can have the effect of unjustifiably favouring some options over others. A better approach, and one which provides a more accurate comparison with other ways of supplying a similar service (e.g. electricity), is to present costs in terms of a unit of product, e.g. $/MWh, coupled with the CO_2 emissions per unit of electricity generated (e.g. in tCO_2/MWh). For completeness this should take account of the costs and energy use of the transportation and storage parts of the system as well as capture - the cost of shipping 10 Mt/y CO_2 over 250km in an offshore pipeline would be about $3/t CO_2-transported. The cost of injection for storage is estimated as up to about $8/t CO_2-injected, although this is site specific. In large quantities, monitoring should cost less than $1/t CO_2-stored, levelled out over the life of a project. In comparison with these figures, the cost of capture is at least an order of magnitude larger.

30. Because of the variety of influences on cost, such data are not presented here in detail – the interested reader is referred to other, more extensive reports, such as the Inter-governmental Panel on Climate Change (IPCC) Special Report on CO_2 capture and storage, for more specific

information. This shows that the cost of generating electricity in a plant with capture and storage is typically $10-50/MWh more than in similar plant without CCS; the precise value depends on the circumstances of the application[1].

31. Most of the published studies of specific projects consider particular CO_2 sources and particular storage reservoirs. Necessarily these plants handle only a few million tonnes of CO_2 per year. Although these are realistic quantities for the first commercial projects, they fail to reflect the potential economies of scale that are likely to be found if/when this technology is widely used for mitigation of climate change. Under those circumstances, much greater quantities of CO_2 would have to be captured, transported and stored, with commensurate reduction in cost.

32. It can be expected that, over a period of several decades, the cost of CCS will continue to decline as a result of both economies of scale and increased experience in the manufacture and operation of most stages of the CCS system.

V. REASONS FOR CURRENT INTEREST IN THIS TECHNOLOGY

33. Emissions of CO_2 are continuing to rise (on a global basis) due to the continuing growth in energy consumption. Fossil fuels provide 86% of the energy used worldwide and account for about 75% of current anthropogenic CO_2 emissions. Global CO_2 emissions have grown at a rate of 1.0% per year between 1990 and 1995 and 1.4% between 1995 and 2001. Atmospheric concentrations of CO_2 are now about 380 ppmv compared with 280 ppmv before the Industrial Revolution. The amount of other GHGs produced by human activities (e.g. methane, nitrous oxide, fluorocarbons, etc.) has also increased. It is widely accepted that these changes have contributed to a rise in global average temperatures – according to the IPCC "there is new and stronger evidence that most of the warming observed over the past 50 years is attributable to human activities." It further states that "human influences will continue to change atmospheric composition throughout the 21st century." As a result "global average temperatures and sea level are projected to rise under all … scenarios"[2].

34. In order to address these changes, 189 nations have ratified the UN Framework Convention on Climate Change (UNFCCC). This proposes that the world should aim to limit the concentration of GHGs in the atmosphere to a level that would prevent "dangerous anthropogenic interference with the climate system".

35. Global CO_2 emissions from fossil fuel consumption and flaring of natural gas were 24 $GtCO_2$/y in 2001 – industrialized countries were responsible for 47% of energy-related CO_2 emissions (not including international bunkers). The economies in transition accounted for 13% of 2001 emissions; emissions from those countries have been declining at an annual rate of 3.3% per year since 1990. Developing countries in the Asia-Pacific region emitted 25% of the global total of CO_2; the rest of the developing countries accounted for 13% of the total[1].

36. Given the major role played by fossil fuels in supplying energy to modern society, and the long time involved in making changes in energy systems, the continued use of fossil fuels is arguably a good base-case scenario. In a large number of scenarios[3] surveyed by IPCC, the cumulative totals of CO_2 emissions over the 21st century are projected to lie in the range of 3,480

to 8,050 $GtCO_2$ depending on scenario. Comparison with the estimated capacity of geological formations (see above) indicates that CCS could help to avoid a significant fraction of these emissions[1].

VI. OPTIONS FOR MITIGATING CLIMATE CHANGE

37. IPCC's Third Assessment Report showed that, in many of models of energy and climate, the achievement of stabilisation at a level of 550 ppmv would require that global emissions be reduced by up to 70% by 2100, compared with the level of emissions in 2001. If the target were lower (450 ppmv), even deeper reductions (55-90%) would be required. It may be helpful to consider the major factors influencing CO_2 emissions – the following simple identity shows the main influences on emissions from supply and use of energy (after Kaya):

$$CO_2\, Emissions = Population \bullet \left(\frac{GDP}{Population}\right) \bullet \left(\frac{Energy}{GDP}\right) \bullet \left(\frac{Emissions}{Energy}\right)$$

38. This shows that the level of CO_2 emissions depends directly on the size of the human population, on the level of global wealth, on the energy intensity of the global economy, and on the emissions arising from production and use of energy. At present, global population continues to increase, average energy use is also rising, whilst the amount of energy required per unit of GDP is falling in many countries but only slowly. So, achieving such deep reductions in emissions, all other aspects remaining constant, will require major changes in the third and fourth factors in this equation, the emissions from energy technology. Thus meeting the challenge of the UNFCCC's goal will require energy technology with strongly decreased emissions.

39. A wide variety of technological options have the potential for reducing net CO_2 emissions and/or atmospheric CO_2 concentrations, including improving energy efficiency and switching to lower carbon or no-carbon fuels; further options may be developed in future. The targets for emission reduction will influence the extent to which each technique is used. The extent of use will also depend on factors such as cost, capacity, environmental impact, the rate at which the technology can be introduced, and social factors such as public acceptance.

40. The contribution that CCS could make to reducing emissions will be influenced by factors such as its cost relative to the other options, the means of transportation to storage sites, environmental concerns, and the acceptability of this approach. The CCS process requires additional fuel which will generate extra CO_2 compared with a similar plant without capture. In addition there are barriers and constraints to use of this option that are discussed in the next section. Whilst it is very likely CCS could make a useful contribution to reducing GHG emissions, the scale of the problem is so large that many different measures will need to be used together.

VII. CHALLENGES AND BARRIERS TO IMPLEMENTATION OF CO_2 CAPTURE AND STORAGE PROJECTS

41. Given that the technology of CCS is feasible, in order for it to contribute to mitigation of climate change a number of challenges will have to be overcome – for example, there must be a

recognised need for it; there must be general confidence that it can deliver the emission reductions expected; and there must be a means of paying for it.

42. In order for CO_2 to be injected into a geological formation, various regulatory and legal requirements will have to be satisfied, especially if the CO_2 is to be accepted as being stored for purposes of protecting the climate. Some of these requirements are clear – the storage must be safe and secure; it must be possible to verify the amount of stored CO_2; and there must be minimal impact on the environment (both the local environment and the global climate). Due to the long time involved, especially in relation to climate impact, models of the physical and geochemical behaviour of CO_2 in the formation will be key tools in verifying that these requirements are met.

43. Some of these challenges and barriers can be identified now, but others may not become clear until such projects are carried out commercially. Potential operators of such projects will need to know that they can be carried out legally, there is a means of paying for them and they can calibrate the potential liabilities. Governments have comparable, but different needs.

(a) Legal issues

44. An important question is what regulations and laws will apply? This is best addressed separately for the capture part and the transmission and storage part of the system, because of their very different natures. Various existing regulations will be relevant, e.g. those covering mining, waste disposal, drinking water, pipelines, etc. but analysis of existing regulations in North America, Europe, Japan and Australia has shown there is a lack of specific regulations addressing CO_2 storage.

45. For planning and operation of a plant with capture, the relevant rules and regulations will be similar to those of other large chemical plant; there may be planning issues; certain types of capture process may present health and safety concerns. The capture system may produce some waste material so the environmental impact of the plant will also have to be examined. An environmental impact assessment is likely to be needed in order to gain planning permission.

46. For the transmission and storage parts of the system, there are likely to be local interests that will be expressed in the public planning process. Health and safety and other operational issues will be regulated as for other high pressure gases – CO_2 can be dangerous to human or animal life if allowed to accumulate in high concentrations. Such concerns will influence the design of the installations – for example, the maximum distance between check valves on a pipeline will be chosen so as to limit the amount of gas that could escape in the event of an accident (and hence the potential risk to people).

47. Depending on the type of geological reservoir used, there may be property and mineral rights and regulatory requirements concerning use of the surface and sub-surface. This may require payment of some form of royalty for use of the reservoir, and perhaps compensation for sterilisation of the reservoir. There may also need to be compensation to existing rights holders for any exposure to liability arising from storage of CO_2. The question of who owns the CO_2 stored underground would have to be clear and whether the rights to the pore space can be transferred to another party.

48. If, as seems likely in Northern Europe, the CO_2 is stored under the sea, international law will be involved. As a general principle, States exercise sovereignty in their own territories and have responsibility to ensure that activities within their jurisdictions do not cause transboundary impacts. International agreements that may have implications for CO_2 storage include the London Convention and its 1996 Protocol, the Basel Convention on transport of hazardous waste, and the UN Convention on Biological Diversity. Regional agreements such as the OSPAR Convention, the Helsinki Convention and others will also be relevant - the current interpretation of the London and OSPAR conventions is that they would apply to CO_2 stored in reservoirs deep beneath the seabed. The treatment of CO_2 storage under some of these Conventions is currently the subject of discussion between the Parties involved.

49. In addition to these issues, which are typical for planning any major plant, there is also a longer-term aspect, because of the climate benefit of CCS. It will be necessary to consider issues such as the potential effects of leakage on achieving the goal of climate change mitigation, as well as the health, safety and environmental implications of any leakage from CO_2 storage over the long-term.

(b) Commercial barriers

50. Almost any mitigation measure, by reducing GHG emissions, is likely to increase the operators' costs compared with business as usual. There may be compensating benefits (for example improving energy efficiency can result in cost savings) but, in general, as the depth of emission reduction increases, so does the net cost. In recognition of this, various means of encouraging operators to implement such actions have been developed. One way is a straightforward tax on excess emissions – some CCS schemes have already been implemented under carbon-tax regimes (although not yet for power generation projects). There are also three so-called flexible mechanisms under the Kyoto Protocol, which will be described later. In principle any of these could provide opportunities in certain countries to support implementation of CCS projects.

51. There may also be opportunities to generate some offsetting revenues from use of CCS – the most clear-cut case being enhanced oil recovery (EOR) as this is based on established commercial practice. It has also been suggested that the injection of CO_2 into new gas fields could enhance gas production by maintaining pressure instead of letting it decline – the first injection into a new gas field is taking place at the In Salah gas field in Algeria. Injection into coal beds could enhance coal bed methane recovery – the first demonstration of this took place at a commercial coal bed methane project in the San Juan Basin in the USA; a European Commission (EC) funded project has been testing a site in Poland to see if the technique would be feasible there.

VIII. AN OVERVIEW OF INSTITUTIONAL AND COMMERCIAL NEEDS

(a) International funding mechanisms

52. The three flexible mechanisms introduced in the Kyoto Protocol are International Emissions Trading, Joint Implementation, and the Clean Development Mechanism. These instruments enable countries to enter into agreements to cut GHG emissions in other countries, if this can be done at a lower cost than would be possible at home. In principle any of these

mechanisms could be used to support CCS projects. Application of these mechanisms for CCS, however, was not considered until the 11th Conference of the Parties (COP) in 2005.

53. Emissions Trading can be used by countries which have accepted emission reduction targets (often referred to as “caps”) under the Kyoto Protocol. Reductions in emissions below the cap can have commercial value, in that these reductions can be traded between countries. The caps can be translated into limits on emissions by individual commercial enterprises in those countries, which enable them to trade emission reductions or rights to emit. The most developed system of trading is the European Emissions Trading System (ETS). The acceptability of CCS under the ETS has been considered by some countries; it is thought that the ETS may be able to recognise emissions reductions from CCS in future, perhaps in the 2008-2012 period.

54. The Clean Development Mechanism (CDM) and Joint Implementation (JI) are project-based mechanisms. They are intended to contribute to the economic development of the host countries, through the transfer of environmentally sound technology. Annex I countries which do not have quantified emission reduction targets (e.g. one of the economies in transition) may be able to gain support for using CCS technology through Joint Implementation. Developing countries may be able to gain support for transfer of CCS technology and gain experience with it through the Clean Development Mechanism.

55. It was agreed at the 2005 COP/MOP (Meeting of the Parties to the Kyoto Protocol) that a CCS workshop would be held at the May 2006 SBSTA (Subsidiary Body for Scientific and Technological Advice) meeting; the remit of this workshop was to provide guidance on CCS for both the Clean Development Mechanism and the World Bank’s Global Environment Facility.

56. So far few CCS projects have been proposed for support under the flexible mechanisms, but the difficulties encountered by some other types of project (such as afforestation) indicate the type of institutional problems which may have to be faced.

57. The key element for a CDM project is a calculation of how the GHG emissions would have evolved in the absence of the CCS project. Reduction in GHG emissions beneath this baseline level would provide credits, which the funding country can offset against its own commitments. There are many issues to be considered for a CCS project to be accepted under CDM or JI. The current low value of Certified Emission Reductions is a major barrier to such projects at present. The permanence of storage is a question which has still to be resolved for these projects but the long retention time of geological formations may make it easier for CCS to be accepted under CDM than was the case for natural sinks, such as afforestation, where the retention time is relatively short. A number of countries may have potential to host CDM or JI projects involving CCS, but the true potential can only be assessed once their underground storage resources have been mapped. It is possible that some CO_2-EOR projects could become more attractive by the addition of CCS, especially if the project resulted in a delay in abandonment of an oil field or if it avoided job losses, but until specific rules are decided this can only be speculation.

(b) Accounting for the stored CO_2

58. A key issue for regulators and for the operators of CCS schemes will be how to account for the stored CO_2. Some of the complexity of this problem can be understood by considering what

happens to the CO_2 once it is in the geological formation – initially the CO_2 will be separate from the formation fluids, dissolving over time to an extent which depends on the nature of the fluids (e.g. CO_2 dissolves better in oil than in water). Some of the CO_2 may move under the influence of any natural flow through the geological formation although it is expected this would be slow if the reservoir is one which is regarded as well suited for storage. Eventually some of the CO_2 will be locked up by reaction with the reservoir rock or by trapping in the pore spaces. So, as time passes, it may be more difficult to identify precisely where the CO_2 is and hence confirm the amount of CO_2 in the reservoir, even if there has been no leakage from the reservoir. It may also be difficult to account for the CO_2 coming from a particular source if it mixes with other stored CO_2. Hence, it will be important to establish clear responsibilities for the stored CO_2 which will likely require an appropriate organisation to oversee the storage, not only during the injection period but also later on.

59. As yet, the requirements for accounting for the stored CO_2 have not been established. The first priority for any monitoring will be to determine the baseline level of CO_2 in the environment and to describe the storage reservoir and its surroundings before injection. Once injection has started, monitoring will be needed to confirm the integrity of storage, both for reasons of commercial accounting as well as to engender public confidence in the retention of the CO_2. This will also provide the basis for any penalty on the operator in the event that CO_2 escapes. However, the danger of escape will be very much affected by the manner in which the store is operated, so regulation may be needed to distinguish between acceptable and unacceptable behaviour, including the keeping of appropriate records. Records may also be needed for assessment of royalties and/or dues, determination of rights, and avoidance of any subsequent inadvertent disturbance of the CO_2. Identification of a responsible organisation that will undertake these responsibilities in the long-term is also important.

60. There will be a trade-off between the costs of site selection and characterisation, the costs of accounting for the stored material and the long-term liability presented by the stored CO_2.

(c) Understanding the risk of CO_2 leakage

61. As with any gas, it is possible that CO_2 could leak from the transmission or storage system. The impact of CO_2 leakage should be considered from two different perspectives: as a direct health and safety threat or as a reduction in the effectiveness of the mitigation measure.

62. For transportation, the potential hazard of CO_2 leakage would have to be carefully managed but in the USA, where there are thousands of kilometres of CO_2 pipeline in operation, no fatalities were reported as arising from these pipelines in the 12 years up to 2002.

63. For storage, a risk assessment may be needed to satisfy the authorities and others about the safety of the storage facility. It is thought that the most likely route for a significant leak would be via the well-bore of a well drilled into the formation. In order to calibrate and check the risk assessment models, monitored data from real-life injections will be essential. This is one of the main reasons why several commercial CO_2 injection projects involve monitoring of the CO_2 in the reservoir or may do so in future (see below).

64. Any scheme to store CO_2 only has merit if the CO_2 is sequestered for hundreds or thousands of years. This indicates that the storage reservoir must be gas tight, certainly

sufficiently tight to avoid leakage of more than, say, 0.1% per annum and probably much less; this level of leakage would be consistent with the capability of well-chosen geological reservoirs to retain CO_2. Without this ability, the storage concept would be invalidated and there would be no point in describing it as a climate protection measure. Even if there is little or no leakage, there may be concern about catastrophic failure, suggesting that the storage system should be designed in a similar way to natural gas storage systems, probably choosing a location well away from centres of population.

65. Last, but certainly not least, it will be important that the public can accept this means of supplying energy with much reduced impact on the climate. At present, the general public is not well informed about CCS. The few studies of public attitudes carried out so far suggest that this technology may be less favourably viewed than some other mitigation options, such as improving energy efficiency or expanding the use of renewables. People seem to have particular reservations about the idea of ocean storage. Very little has been done to inform the public in many countries about this technology with some exceptions, such as the Netherlands and Norway, where public understanding is more advanced and the advantages of capture and storage of CO_2 are better understood.

IX. EXISTING PARTNERSHIPS AND INTERNATIONAL ACTIVITIES

66. Despite the relatively limited period in which much attention has been given to this technology, there are already several large-scale storage projects in operation or in planning (Table 2). For example, over nine million tonnes of CO_2 have been stored to date in a deep saline reservoir under the Norwegian sector of the North Sea in a project which began in 1996. The CO_2 is separated from natural gas produced from the Sleipner West gas field. This is the first large-scale, purposeful storage of CO_2 for reasons of protecting the climate.

Table 2. Commercial CO_2 Injection Projects with Monitoring of Stored CO_2

Project	**Country**	**Storage Type**	**Injection Start Date**	**Injection Rate (t/year)**	**Measurement Project**
Sleipner	Norway	Saline formation	1996	1 million	SACS, CO2STORE
Weyburn	Canada	EOR	2000	1.1 – 1.8 million	WEYBURN
ORC phase 2	Netherlands	Depleted gas field	2004	20 000	CO2REMOVE
In Salah	Algeria	Producing gas field	2004	1 million	IN SALAH
Snøvhit	Norway	Saline formation	2006	0.75-0.95 million	To be decided
ORC phase 3	Netherlands	Depleted gas field	2006	0.48 million	To be decided
Gorgon	Australia	Saline formation	2009	2.7 million	To be decided

67. Other commercial CO_2 injection projects also use CO_2 separated from natural gas streams. Such CO_2 would normally be vented to the atmosphere but the operators of several projects have decided to re-inject the CO_2 underground, including the ORC project (the Netherlands) and In Salah in Algeria. Future projects of this type include Snøvhit (Norway) and Gorgon (Australia).

68. Such projects are potentially valuable opportunities to learn about the behaviour of injected CO_2. If these can be monitored in a collaborative project, this enables many organisations to learn from the one project; this is being carried out in several projects, the first of which was the Sleipner injection.

69. Another type of project is that based on use of CO_2 for EOR; the Weyburn project in Canada is currently the only commercial EOR project with monitoring of the stored CO_2. This started operation in 2000. CO_2 captured in a large coal gasification project in North Dakota, USA, is being transported by pipeline and injected into the Weyburn field in Saskatchewan, Canada. Initially 5,000 tonnes per day of CO_2 are being injected. An international research project aims to determine how effective this CO_2 storage will be over the long-term. The Rangely-Webber EOR project in the USA has been studied to find out whether any of the injected CO_2 is leaking to the surface – no significant amount has been detected.

70. A pilot CO_2-enhanced coal bed methane project, the Allison Unit in New Mexico, USA, operated for 3 years. Although not set up for purposes of storage (the CO_2 came from a natural source), this project provided some demonstration of the potential. A field test of enhanced coal bed methane production using CO_2 and nitrogen mixtures is being carried out in Canada by the Alberta Research Council. Such a combined approach may improve the prospects for recovering methane and storing CO_2.

71. Some injections have been undertaken purely for reasons of research – necessarily these projects are more limited in extent than the commercial projects but provide valuable information for future storage design and monitoring. To date, monitored injections have taken place at West Pearl Queen and Frio in the USA and Nagaoka in Japan. Several more research projects are in preparation.

72. Another key aspect is to find the best storage sites and estimate their capacity. A survey of geological resources in Europe has been undertaken under the GESTCO project, which assembled a database of potential resources in Northern Europe; the GeoCapacity project is extending this work to eastern, central and southern Europe. Similar projects are underway in other parts of the world.

73. In contrast to the research on storage, work on capture tends to involve fewer international collaborations because, in many cases, the technology is proprietary - for example, Mitsubishi Heavy Industries have developed several improved solvents; Fluor-Daniel has improved heat integration to reduce capture costs; the CCP (CO_2 Capture Project), largely industrially funded, examined many capture options and instigated some work on novel methods. Nevertheless, several EC funded projects are exploring novel technology (e.g. AZEP) or developing major facilities in which capture equipment can be tested (e.g. CASTOR and ENCAP). Outside Europe there are other such programmes, e.g. the CO_2 capture R&D programme at the University of Regina in Canada, which includes participants from outside Canada.

74. Collaboration on these activities is often organised or coordinated through international programmes – the one with the longest history is the IEA Greenhouse Gas R&D Programme, which was established in 1991 and involves industry and government from many different countries. More recently the Carbon Sequestration Leadership Forum (CSLF) has been established in order to facilitate collaboration on issues of technology, policy and public outreach. Regional programmes, such as the EC's Framework Programme and, more recently, its Technology Platforms provide opportunities for collaborative research and networking; the EC has supported a significant amount of activity in this field over several years. National programmes such as those in Australia and Canada and elsewhere have also put emphasis on establishing international links.

X. POSSIBLE ROLES FOR THE UNECE

75. Many UNECE member States are Parties to the UNFCCC and many of them have made reductions in GHG emissions. Nevertheless their per capita emissions are still amongst the highest in the world. Thus it would seem likely that members of UNECE would be interested in cost-effective methods of reducing GHG emissions, even if not for application immediately.

76. There are recognised opportunities for reducing emissions in the countries of Eastern Europe, Caucasus, and Central Asia (EECCA) through improvement in energy efficiency, however policy barriers, the lack of adequate financial engineering skills and inappropriate financing mechanisms are all thought to have delayed the uptake of such measures. Similar constraints will apply to CCS projects.

77. It is suggested that possible roles for the UNECE in connection with CCS could include:

(a) To facilitate the surveying and qualification of suitable storage sites.
(b) To ensure that CCS is understood sufficiently in member States so that it can be considered in an equivalent way to other, more familiar mitigation options.
(c) To identify gaps in skills relevant to defining CCS project opportunities in member States. This could be initiated through a series of workshops to introduce the technologies to the relevant technical communities.
(d) To seek opportunities for application of CCS technology, in particular by assessing the feasibility of application in large central plants, and to identify suitable geological storage sites, especially where there might be geological formations that provide advantageous conditions such as depleted oil fields.
(e) To identify and facilitate opportunities for funding through International Emissions Trading and/or Joint Implementation.
(f) To assist member States to develop norms and standards to integrate CCS into their regulatory structures, including environmental regulations.

Endnotes

[1] IPCC Special Report on CO_2 Capture and Storage (2005)
[2] IPCC Third Assessment Report (2001)
[3] Future emissions may be simulated using scenarios. Scenarios are useful tools to analyse the influences on future emissions but they are not forecasts. They are particularly useful in considering long-term changes in energy supply and use because of the large uncertainties.