IEA
Greenhouse Gas
R&D Programme





Phase 4 Summary Report

Background

This document was issued as a summary report at the conclusion of Phase 4 of the IEA Greenhouse Gas R&D Programme (IEA GHG).

IEA GHG is a cost-sharing Implementing Agreement operating under the aegis of the International Energy Agency (IEA). Members contribute annually to a common fund. Since 1974 the IEA has provided the Implementing Agreements (IA) structure as a route to international co-operation on energy issues. There are currently some 40 active programmes. The IA framework provides a legal mechanism for establishing the participants' commitments and a management structure.

There are 2 categories of participant in an IA:

- Contracting Parties can be governments or entities nominated by them. They can also be international organisations in which governments participate.
- Sponsors are private sector entities which have not been designated by a government.

IEA GHG has an Executive Committee (ExCo) of representatives nominated by the Contracting Parties and Sponsors. The ExCo acts as a management board to decide on the work programme and supervise the use of the common funds.

Operational management of IEA GHG is assigned to an Operating Agent who is accountable to the ExCo. The Operating Agent is IEA Environmental Projects Ltd., a UK registered company.

For details about participation or any other aspect of the programme please contact Harry Audus, General Manager, IEA Greenhouse Gas R&D Programme at the address given on the back page.

Cover Pictures

Schwarze Pumpe Power Plant. Courtesy of Vattenfall AB
CO2 Capture at Nanko Power Plant, Japan. Courtesy of Kansai Electric Power Co.
CO2 Compressors at Dakota Gasification. Courtesy of Basin Electric Power Cooperative.
CO2 injection facilities at the RECOPOL project site in Poland.
Sleipner CO2 storage facilities. Courtesy of Statoil
The back cover shows membership of the IEA GHG Programme at the end of Phase 4.

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Introduction

The members of the IEA GHG Programme (IEA GHG) have been active for 13 years in assessing and encouraging the development of CO_2 mitigation technology.

Over that period, they have succeeded in achieving widespread acceptance that carbon dioxide capture and storage (CCS) is one of the key options needed to obtain deep reductions in the emission of CO_2. CCS was merely a technical possibility when IEA GHG started in 1991 (see Table 1); it is now firmly on policymakers' agendas.

IEA GHG members recognise the major role that fossil fuels play in underpinning world economic development. Through the programme's work they have demonstrated the opportunity for the continued use of fossil fuels even under emission scenarios involving deep reductions in the emission of greenhouse gases.

Timescale	**Basic Technology**	**CO2 Capture**	**CO2 Utilisation & Storage**
Near-term	PF coal, Natural gas combined cycle	Absorption, adsorption, indirect biofixation	Enhanced oil recovery, exhausted oil & gas wells, chemical feedstock
Medium-term	Integrated gasification combined cycles	Cryogenics, membranes	Aquifers & salt domes, new chemicals/fuels
Long-term	Oxyfuel, fuel cells, topping cycles	Advanced systems	Direct biofixation, solid disposal

Table *1: Original (1991) table showing the initial scope of IEA GHG technical assessments*

By the end of 2005, IEA GHG had completed over 100 studies on behalf of its members. The core of the study work has focused on CCS, but many other areas are covered; for example, comparisons with other emission reduction options, and alternative energy carriers.

Work by IEA GHG quickly established that CO_2 could be captured from major emission sources such as power stations. However, the solution to the question of secure long-term stores was far from clear. IEA GHG's first conference was held in Oxford, in 1993 and its main objective was to identify the prospects for credible CO_2 stores. At this conference the emphasis was on ocean storage but a few visionary papers described how CO_2 could be stored deep underground. The successors to this conference have now grown to be major biannual events: The GHGT series of International Conferences on Greenhouse Gas Control Technologies.

Slepiner production platform. (Courtesy of Statoil)

The major achievement for CCS technology over the last few years has been to demonstrate, on a large scale, that CO_2 can be stored underground. Major projects, initially at Sleipner in the North Sea, and subsequently, at Weyburn, Canada have demonstrated that CO_2 can be stored underground safely and its storage monitored (Figure 1).

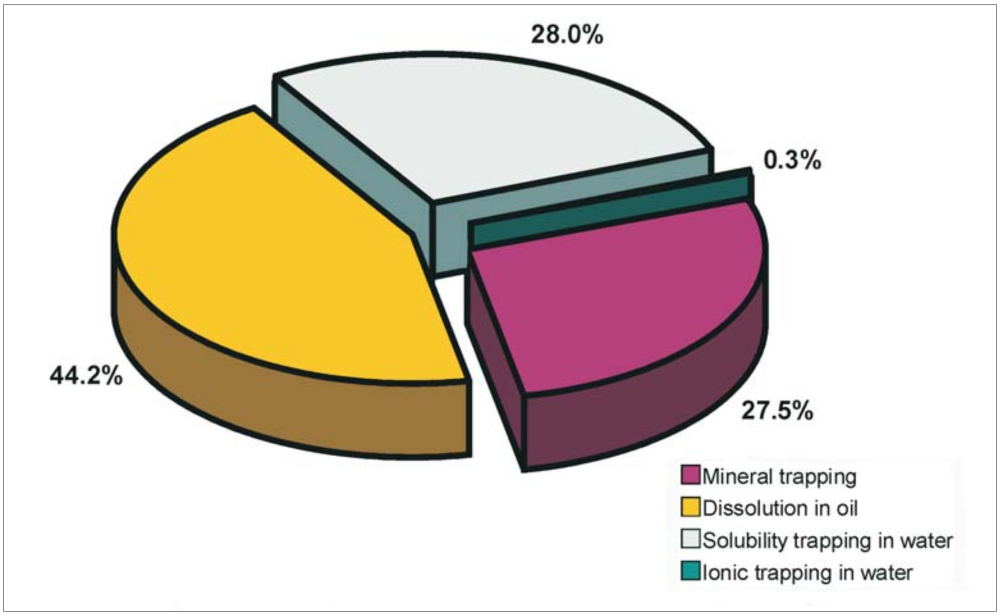


Figure 1: Potential distribution of CO2 in the Weyburn reservoir after 5000 years (from Wilson M, Monea M, (eds) IEA GHG Weyburn CO2 monitoring and storage project summary report 2000-2004)

With the commencement of the In Salah CO_2 storage project in 2005 something of the order of 3 million tones per year of CO_2 is being stored underground and its location monitored (Figure 2).

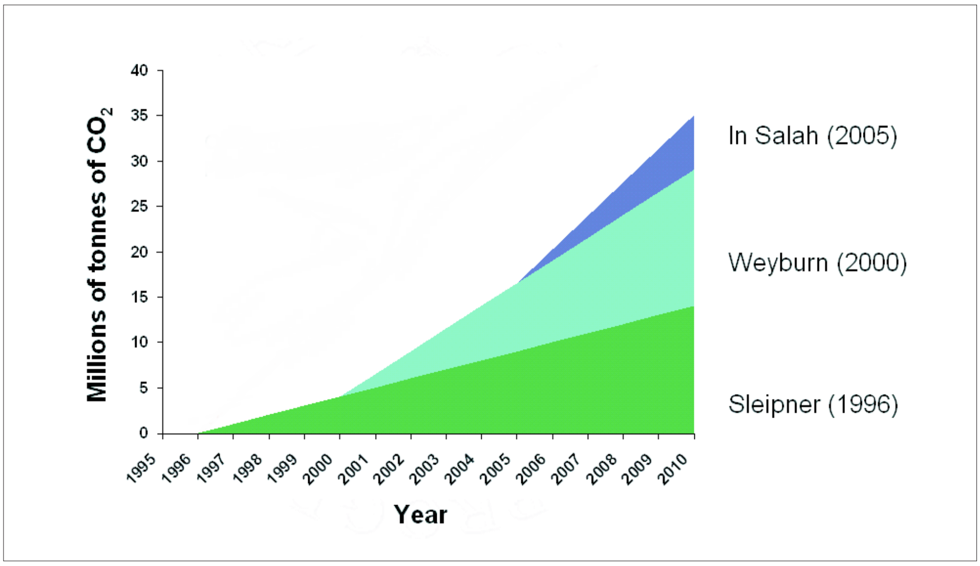


Figure 2: Cumulative amount of monitored CO2 storage

Progress towards the establishment of CCS technology is expected to accelerate during Phase 5 of the IEA GHG Programme. Indeed, it will have to, if CO_2 emissions are to be stabilized. at the same time as the world's energy needs and dependence on fossil fuels continues to increase (see Figure 3). This will be a challenging time for IEA GHG and its Members.

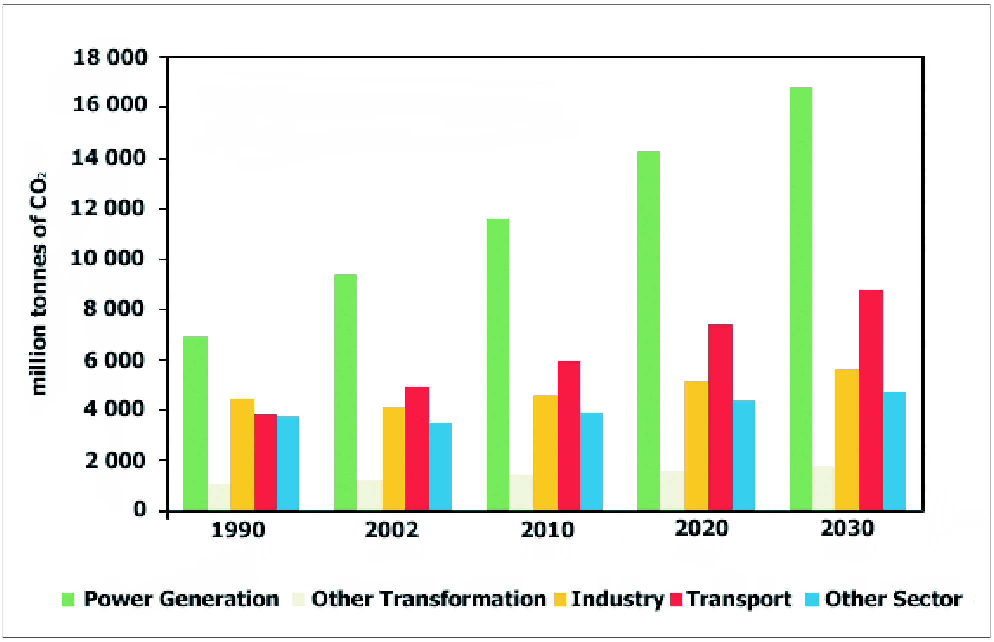


Figure 3: Projections of CO_2 emissions by sector from IEA World Energy Outlook 2004. Note that emissions from power generation are projected to continue to dominate and that transport is projected to be a major emission source of increasing importance. IEA GHG work has shown the potential for carbon capture technology in both these areas. For transport applications, CCS can be used to produce either low-carbon electricity or hydrogen.

The need now is for large scale demonstrations of the integrated technology from capture through to storage.

There are many outstanding issues still occupying the programme membership. Amongst the key issues are:

- Driving down the cost of capture
- Development of confidence in underground storage

As the new phase develops IEA GHG will be working on these and other issues to ensure that CO_2 mitigation options can be compared and that CCS can be safely and legally introduced at commercial scale.

Programme Membership and Organisation

Over its 13 year life IEA GHG has built up a reputation as the premier source of unbiased information on the options available to reduce emissions of greenhouse gases to the atmosphere. The programme aims to produce policy relevant information but is not policy prescriptive. Members are drawn from a wide range of countries and industrial entities each with its own policy drivers. The main benefits of participation include:

- Contributing to the development of the work programme and by doing so introduce perspectives from an international range of national and industry sources.
- Access to unbiased information, obtained from international experts, presented in consistent and transparent evaluations.
- The added benefit of significant leverage on their contributions that can also reduce the potential for having to duplicate the efforts of others.
- IEA GHG is one of the International Energy Agency's (IEA) Implementing Agreements (IA). Operation under the aegis of the IEA gives members the assurance of, and a route to participate in, the IEA's comprehensive international programme of energy co-operation.

It is a key strength of the IEA GHG Programme that it has participants from both country governments and private sector entities. This provides a forum for perspectives from an international range of national and energy industry sources. Because of this range of views the activities of the programme are seen to be widely relevant and acceptable.

The advent of the Kyoto Agreement in February 2005 renewed world-wide activities on the climate change problem. Despite the reservations that some have about the Agreement, it is clear that one result is to focus policymakers' attention on the next generation of energy technologies. Signatories to the Agreement have agreed to:

"Research on, and promotion, development and increased use of, new and renewable forms of energy, of carbon dioxide sequestration technologies and of advanced and innovative environmentally sound technologies".

If, as expected, this encourages the search for and development of new CO_2 mitigation opportunities the role of IEA GHG in ensuring that financial and technical resources are used effectively will be of increasing importance.

Phase 4 Achievements

Phase 4 of the Programme finished at the end of 2004. During this phase IEA GHG was heavily involved in moving CCS from the realms of being a technical possibility firmly onto policy-makers' agendas. IEA GHG activities expanded to include research facilitation, research networks, and enhanced communications initiatives. These activities were all aimed at confirming the credentials of CCS as a major option for climate change mitigation.

Studies continued to be the foundation-stone of the Programme's activities. A list of the phase 4 studies is given on page 20. As can be seen from this list the members recognise the importance of both technical and non-technical issues.

Amongst the key studies was one on opportunities for early application of CO_2 sequestration technology (PH4/10, September 2002). 'Early opportunities' is a theme that has subsequently been widely picked-up and developed by others. Similarly, the ground-breaking work on cost curves for CO_2 storage (PH4/9, July 202, and subsequent reports) has had a great deal of influence, e.g. in the preparation of the IPCC's 'Special Report on CO_2 Capture and Storage'. Other key studies assessed potential improvements in both pre- and post- combustion CO_2 capture technology (PH4/19, May 2003; PH4/33, November 2004). These studies set the standard for the assessment of leading technologies for CO_2 capture. This work is to be developed further to compare their relative merits by taking into account practical issues likely to be of interest to power generators.

The first International Research Network network established by IEA GHG was initiated at a workshop in October 2000 in conjunction with the US Department of Energy and ABB Lummus Global. The focus of the co-operative network is on capture of CO_2 using solvents. This initiative by IEA GHG - to establish networks that provide an international forum for researchers in key areas of CCS - has proved a great success. At the time of writing the meetings of CO_2 capture network are still attracting up to 40 participants and the number of research networks has expanded to five. The newest research network in the series the International Monitoring Network started in 2004. The initial objective was to use the results available from projects monitoring injected CO_2 to understand the current state-of-the-art and its limitations. The aim is to develop confidence that injected CO_2 can be monitored and verified and any leakage quickly detected.

IEA GHG's members are interested in promoting practical research, design, and development (R,D,&D) but the programme is not a major source of funds. During Phase 4 the programme assisted in several R,D,&D projects. For example, two CO_2 capture projects in Canada; one on oxyfuel combustion at CANMET, and the other at the University of Regina's International Test Centre. Both were assisted by providing the means for international cooperation in the projects and dissemination of information. Another project in which the programme participated was an industry-led design of a pre-combustion decarbonisation (PCD) power plant; the second stage of this project identified prospects for cost reduction. At the time of writing BP had announced that they intended to proceed with a large-scale demonstration using PCD technology at a power station in Scotland, UK, linked to an oil field in the North Sea.

The initial practical R,D, & D storage project facilitated by IEA GHG was the Saline Aquifer CO_2 Storage research and monitoring project (SACS). This was initiated in 1997 by Statoil in conjunction with IEA GHG. Its objective was to monitor and learn from the world's first commercial-scale saline aquifer storage project. As a result of this project IEA GHG published the 'Saline Aquifer CO_2 Storage (SACS) Best Practice Manual. IEA GHG remains active in this area through participation in the European Commission's CO2STORE project that builds on the earlier work and adds information from new storage prospects.

IEA GHG was also active in the Weyburn EOR project in Canada. This project has produced extensive information about the behaviour of CO_2 in this type of oil reservoir. In 2003 IEA GHG led experts from around the world in an external review of the project. Agreement has been reached that IEA GHG will continue to assist the partners in the second phase of the Weyburn EOR project.

The IEA GHG Programme runs a major conference every two years that is seen as being the premier communication event for workers in the area of greenhouse gas control technologies. Phase 4 of the Programme saw two of these International Conferences on Greenhouse Gas Control Technologies.

Kyoto International Conference Centre, venue for GHGT-6

GHGT-6 was held in 2002 in Kyoto, Japan and attracted 510 delegates from 32 countries. About half the papers were on CCS technology. The other half covered a wide range of subjects including non-CO_2 greenhouse gases, afforestation, biomass and other energy sources, energy policy, etc.

Vancouver Conve ntion & Exhibition Centre, venue for GHGT-7.
(Image courtesy of VCEC)

GHGT-7 was held in Vancouver, Canada, in 2004. This was the largest conference in the GHGT series to date, attracting nearly 670 delegates from 35 different countries. In total some 230 technical papers and 200 posters were presented. In keeping with the progress made in gaining acceptance of the feasibility of CCS as a major option for the reduction of CO_2 emissions, there was an increased emphasis on addressing wider issues. Topics such as risk assessment and legal aspects were allocated sessions and there was a significant number of papers dealing with national action plans to implement CCS. On the final day, there was a special panel session on public perception of CCS at which the results from studies undertaken in the USA, Japan, and the UK were presented. None of the studies suggested fundamental public opposition to CCS.

Current Status of CCS Technology

Capture and Storage of CO_2 is best carried near large sources of emissions (see Figure 4 below). As illustrated in Figure 3 about 30% of emissions at present are from power generation and this percentage is projected to increase. Work is therefore focused on power generation but is applicable to other emission sources.

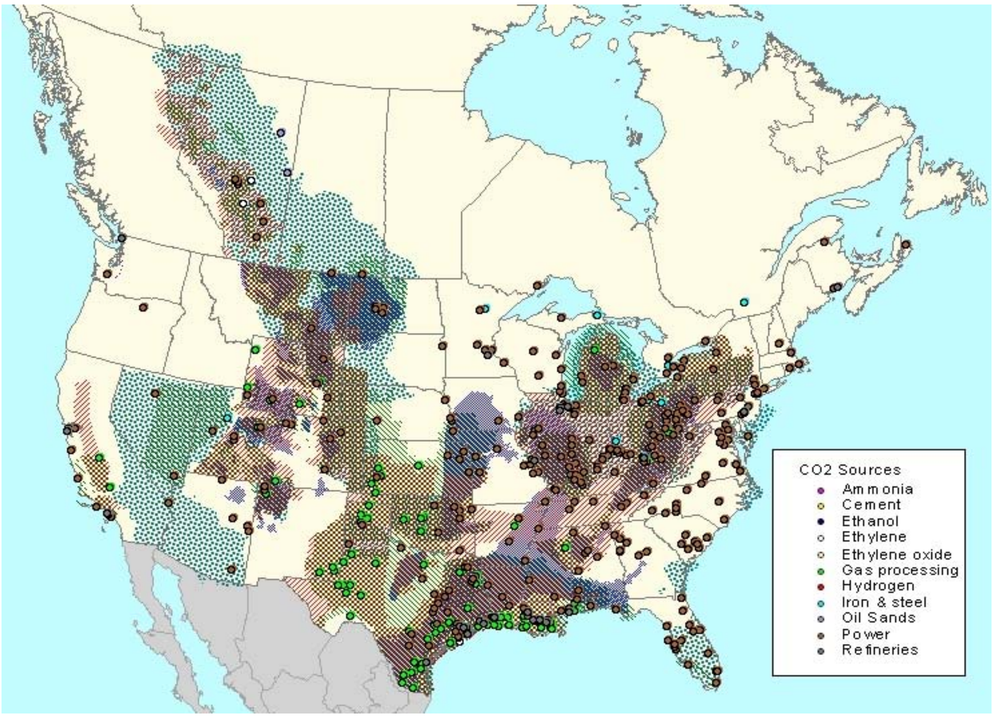
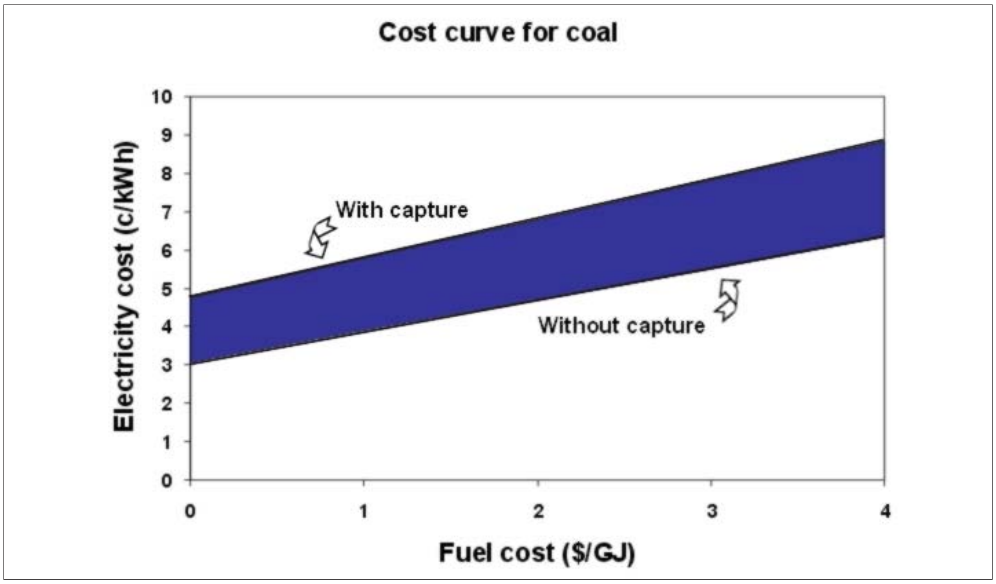


Figure 4 : Matching of CO_2 emission sources and potential stores in the USA (IEA GHG 2005/3 Building the cost curves for CO2 storage: North America)

Capture

Currently, the main technologies used to generate power from fossil fuels are natural gas combined cycles (NGCC) and pulverized coal-fired steam cycles. Work by the IEA GHG and others has established that both these technologies can be adapted to allow post-combustion capture of CO_2 from the power station flue gases. Post-combustion CO_2 capture using amine-based solvents with proprietary additives have been demonstrated in commercial plants but at a much smaller scale and greater efficiency penalty than is required for its application as a CO_2 mitigation option. Figure 5 plots results of recent work by IEA GHG to assess the penalties incurred by adding post-combustion CO_2 capture to new state-of-the-art power plant. For coal-fired power plant, the efficiency would be reduced by 8-9% points and the power cost would increase by about 2 US cents/kWh. In the case of NGCC the efficiency penalty is 6 to 8 percentage points and the increase in cost of electricity about 1.2 c/kWh. These results are for a conceptual plant located on the coast in The Netherlands; other locations and situations will give different results. R&D work in the area of CO_2 capture is aimed at achieving significant reductions in the cost and energy penalties.



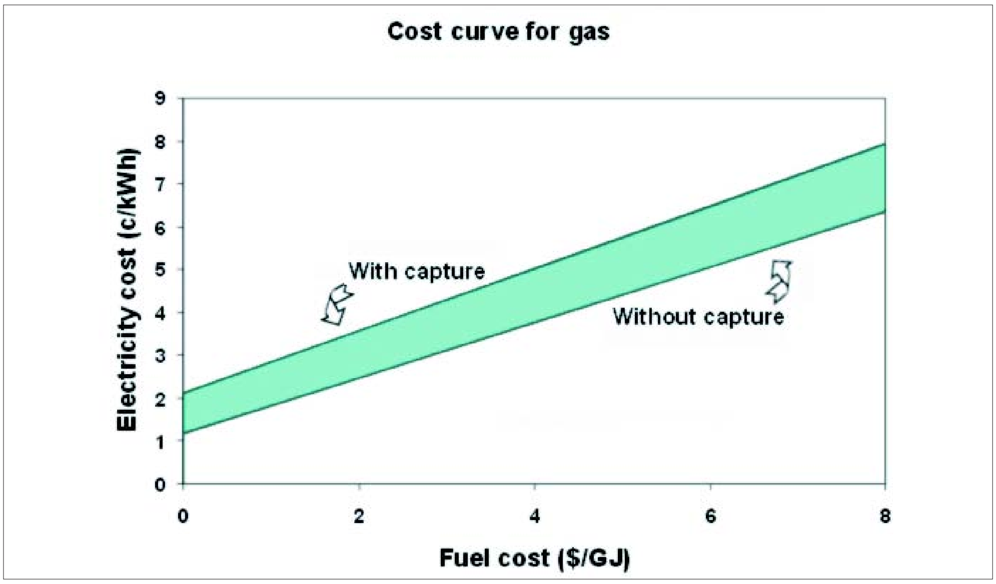
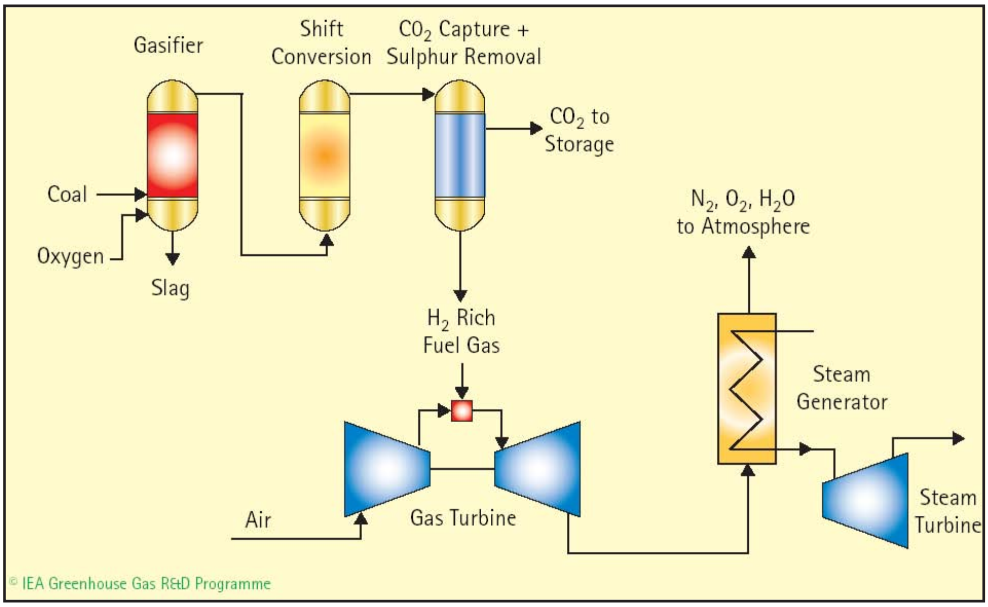


Figure 5 : Results from IEA GHG studies show the penalties incurred by adding post combustion CO2 capture to new state-of-the-art power plant

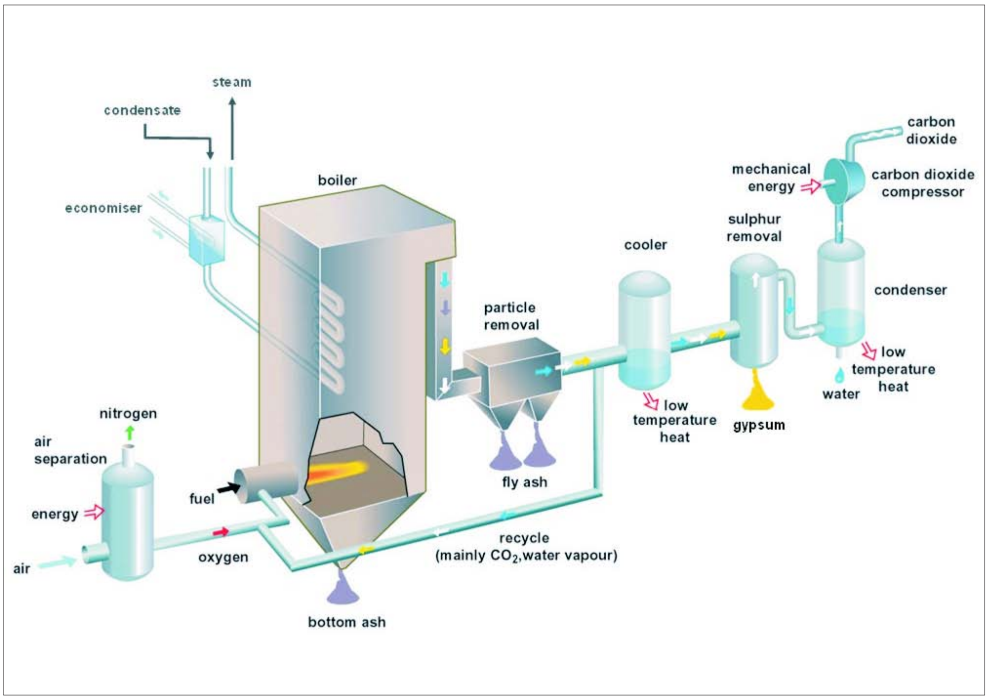
An alternative power generation option, the Integrated Gasification Combined Cycle (IGCC) isre generally agreed to be not yet competitive with coal-fired steam cycles. These cycles are however seen by many as an option that will be increasingly favoured by the drive to near-zero emissions from power plant. In this technology the fuel is reacted with oxygen and steam to produce a fuel gas consisting mainly of carbon monoxide (CO) and hydrogen. Commercial scale gasifiers have been built and there is a significant application for them treating refinery residues. Carbon dioxide can be removed by converting the CO to CO_2 which produces hydrogen by reaction with steam (shift-conversion). The natural gas equivalent is partial oxidation of the fuel. In both cases the decarbonised fuel is hydrogen. This hydrogen is then burnt as an integrated part of the power generation process. In addition, there is the future potential to use the hydrogen as a clean transportable fuel.



IGCC technology can be used to produce either electricity or hydrogen with very low emissions of CO2 to atmosphere.

Adding CO_2 capture to IGCC would increase the cost of electricity by 1-1.5 cents/kWh which is less than for post-combustion capture. But this is starting from a higher base cost for the technology without CO_2 capture.

A third option for capturing CO_2 i.e. oxycombustion is also attracting serious interest. In this option the combustion agent is oxygen diluted with recycled flue gases. Because oxygen is separated from nitrogen before combustion the products of combustion are essentially CO_2 and water which are easily separated. The cost and energy penalties for this option are largely attributable to the production of oxygen.



Process overview of the Vattenfall oxyfuel pilot plant. (Courtesy of Vattenfall)

In terms of projected efficiency and energy penalties there is little to choose between the pre- and post- combustion capture options. Both these options are near-commercial and dependant on large-scale demonstration to make significant progress towards their technical acceptance. Oxyfuel processing is less well developed than the leading 2 options but the penalties appear to be similar and plans for pilot plants are well developed.

IEA GHG is investigating the wider issues that might influence the choice between these 3 options. Overall, it is encouraging that there are 3 technically feasible options by which CO_2 could be captured, provided the necessary incentives were in place and the barriers to their adoption removed. Researchers are working on a variety of additional CO_2 capture options in the hope of reducing the capture penalties. IEA GHG has developed a preliminary screening methodology that can be used to establish whether or not such options have potential.

Transport

Transport of CO_2 from capture point to a store can be done by pipeline or by ship; both these means of transport are used commercially, but not for climate change reasons. The major issues are not technical, but are related to the scale and cost of moving huge amounts of CO_2 from source to sink. IEA GHG have developed a calculator that can be used to estimate costs of transportation. Typically costs are low compared to the cost of capture and lie in the region of 5-10$/tonne of CO_2 for the quantities associated with power generation.

Storage

As highlighted in the introduction, storage underground is now established as a technical option. However, much work remains to be done before it can be widely adopted and accepted. Figure 6 illustrates some of the underground options.

Storage in deep saline aquifers is believed to have the most potential and have a large capacity. However, defining this capacity is proving to be difficult mainly because little work has been done to characterize aquifers.

Storage in depleted oil reservoirs also raises many issues, not least the world’s potential need for greatly increased recovery of oil in place. On one hand there is a near-term opportunity to store CO_2 as a consequence of using it for enhanced oil recovery (EOR). On the other hand, if CO2-EOR is not considered appropriate, a drive to maximize oil recovery could limit the availability of oil fields agreed to be ‘depleted’.

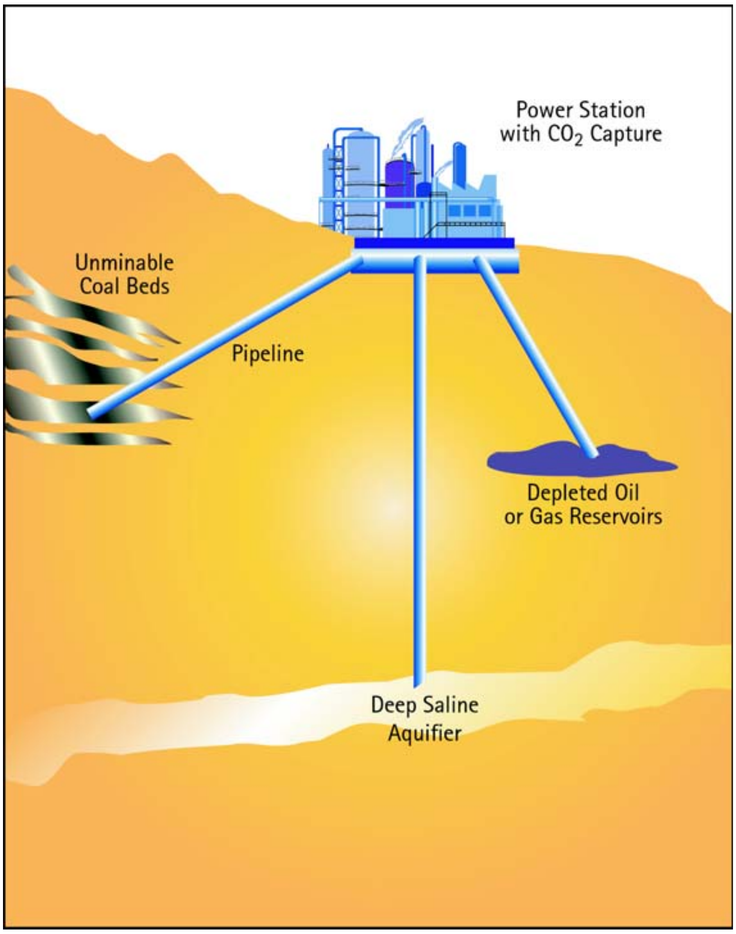


Figure 6 : Options for underground storage of CO2.
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The key issue for underground storage is seen to be risk. There are relatively short-term risks to be satisfactorily dealt with in the areas of health and safety and proving the quantities of stored material. In the longer term there is the problem of responsibility for residual risks after the lifetime of the CCS project. IEA GHG operates one of its Research Networks in this area providing a forum and reference source for R&D activities.

Technology and Market Information

IEA GHG focuses much of its efforts on the production of technology and market information. This study work includes; technical and economic assessments, technology reviews and comparisons, and presentation of papers at key conferences.

In the next phase of the programme IEA GHG will continue to generate information in the following areas:

- Capture and transmission of CO_2
- Safe secure storage of CO_2
- Comparison of mitigation options
- Near zero-carbon energy carriers
- Implementation routes and barriers
- Major energy-using industries

An indication of the depth of activity covered by these brief bullet-points can be gained from Table 2 which highlights some of the implementation issues.

Routes	**Barriers**
Early Opportunities	Acceptance
Implementation Scenarios	Commercial/Financial
Scaling & Timing	Legal
Demonstrations Required	Locational Restrictions
Best practice and standards	Regulatory
	Safety

Table 2 : Implementation routes and barriers

This work is, in the main commissioned from external experts, but in some cases the work is done in-house. Each report is subject to peer review by experts nominated by the members of the programme. This ensures the quality of the work and that it reflects the wide-range of members' perspectives.

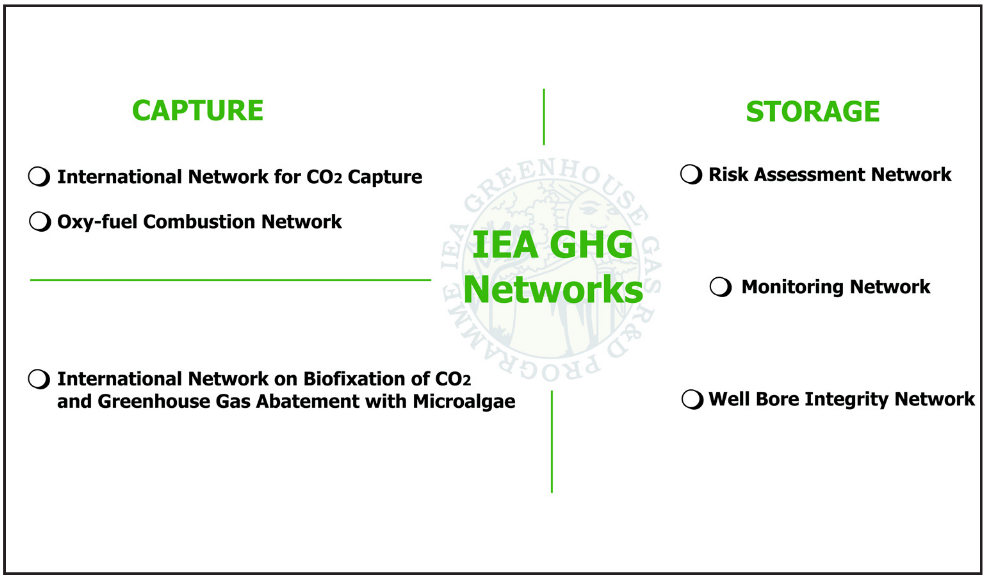
Confidence Building

The programme engages in confidence building by promotion of technology development. Amongst these activities are support for R,D&D programmes by facilitation of and provision of advice, and organization of research networks as forums for themed R&D activities.

Networks

The networks are a means for researchers in specific fields to meet and work on topics of common interest. Each one has goals which are determined by the participants – these may involve, for example, comparing and contrasting methods for CO_2 capture, and preparing guidelines on risk assessment approaches to CO_2 storage.

At the time of writing, a future network on oxyfuel combustion is planned.



Research networks of the IEA GHG Programme

Practical R&D

The practical projects are more varied in their style and content than the networks. In some of these, IEA GHG is instrumental in identifying the gaps, working with others to develop a programme of work, and participating in the subsequent project in an advisory capacity and to handle dissemination. In others, a project leader or funder has approached IEA GHG because of its reputation and invited it to participate; perhaps to contribute in evaluating technology, in providing the international perspective, as a user of the results, or for dissemination (e.g. Weyburn, Recopol, ITC[1], CO2NET2).

In other cases, IEA GHG may have been asked to provide specific help and to provide international publicity. In none of these projects can IEA GHG make a significant financial contribution to the project because the Programme does not have sufficient funds for this.

The programme maintains a database of practical R&D projects that has proved to be a popular reference source. See www.co2captureandstorage.info

CO2 being stored in tanks for injection at the RECOPOL field test site in Poland

1 International Test Centre

Communications

IEA GHG aims at information dissemination to governmental and other policy makers, industry leaders, and public audiences such as environmental NGO's. Deliverables in this area include: Public summary reports, the bi-annual international GHGT conference, a quarterly newsletter, two websites, and maintenance of information databases.

The Programme has the goal of attracting and maintaining participation by a broad range of countries and industrial participants. Input from these participants is important to identify key issues that need to be addressed and ensure the results of IEA GHG's work are widely applicable and realistic. Accordingly, the programme encourages additional participants; further information for prospective members is given on the main website.

IEA GHG members recognised early the importance of the Intergovernmental Panel on Climate Change (IPCC) activities and the IEA GHG Programme was deeply involved in ensuring that CCS was included as a mitigation option in the IPCC's Second Assessment report issued in 1995. IEA GHG continues to be involved. Over the last 2 years the programme team and several members of the ExCo, including the Chairman, have spent considerable effort on the preparation of the IPCC's 'Special Report on CO_2 Capture and Storage'.

Phase 5 – The Challenges

CO_2 mitigation technology has come a long way down the road to commercial application since the IEA GHG Programme started in 1991. However, there is still much to do to enable its commercial take-up on a world-wide scale.

The members of IEA GHG come from a wide range of countries and industrial entities and, despite their varied perspectives and drivers, co-operate very effectively. This spirit of cooperation is in keeping with seeking solutions to a global problem and it is hoped it can be retained as the programme develops.

The adoption of CO_2 capture and storage will always cost money, but there are real hopes that the penalties can be significantly reduced. Ultimately, this reduction will depend on demonstrating the technology in real applications.

Storage of CO_2 and monitoring the stored CO_2 has been shown to be technically feasible. However, there are many outstanding issues to be resolved, amongst them, a key challenge is to gain and retain public acceptance.

In this next 5-year phase of the programme members have agreed to 3 strategic themes:

- Continued generation of technology and market information that is widely accepted as reliable and unbiased
- Increased focus on activities aimed at building confidence in mitigation technology. For example, the Research Networks.
- Improved communications to ensure that information reaches decision and policy makers.

The Project Team

Members of the IEA GHG project team :

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IEA GHG Phase 4 Reports

STUDY	TOPIC
PH4/1	Biofixation with Microalgae for Greenhouse Gas Abatement
PH4/2	Report of a Seminar "Putting CO_2 Sequestration on the Policy Agenda" Organised by CO2NET
PH4/3	CO_2 Technology Scenarios Seminar
PH4/4	International Test Network for CO_2 Capture: Report on 2nd Workshop
PH4/5	Non-CO_2 Greenhouse Gas Network: Inaugural meeting on mitigation technologies and economic analyses
PH4/6	Transmission of CO_2 and Energy
PH4/7	Workbook for Screening of Options to Reduce CO_2 Emissions from Existing Power Stations
PH4/8	Non-CO_2 Greenhouse Gas Network 2nd meeting
PH4/9	Building the Cost Curves for CO_2 Storage - Part I: CO_2 Sources
PH4/10	Opportunities for Early Application of CO_2 Sequestration Technology
PH4/11	International Test Network for CO_2 Capture: Report on 3rd Workshop
PH4/12	CO_2 Abatement by Production and Use of Gas to Liquids Transport Fuels
PH4/13	International Test Network for CO_2 Capture: Report on 4th Workshop
PH4/14	Solar Electricity to Reduce CO_2 Emissions
PH4/15	Acid Gas Injection: A Study of Existing Operations (Phase I: Interim Report)
PH4/16	International Conventions: Implications for CO_2 Storage
PH4/17	Building a Common FEP Database
PH4/18	Acid Gas Injection: A Study of Existing Operations Phase I: Final Report
PH4/19	Potential for Improvement in Gasification Combined Cycle Power Generation with CO_2 Capture
PH4/20	Non-CO_2 Greenhouse Gas Network: Agriculture
PH4/21	Saline Aquifer CO_2 Storage (SACS) Best Practise Manual
PH4/22	International Test Network for CO_2 Capture: Report on 5th Workshop

PH4/23	Barriers to Overcome in Implementation of CO_2 Capture and Storage (2): Rules and Standards for Transmission and Storage of CO_2
PH4/24	Reduction of CO_2 Emissions by Adding Hydrogen to Natural Gas
PH4/25	Building the Cost Curves for the Industrial Sources of Non-CO_2 GHGs
PH4/26	Gas Hydrates for Deep Ocean Storage of CO_2
PH4/27	Canadian Clean Power Coalition Studies on CO_2 Capture and Storage
PH4/28	International Test Network for CO_2 Capture: Report on 6th Workshop
PH4/29	Overview of Monitoring Requirements for Geologic Storage Projects
PH4/30	Ship Transport of CO_2
PH4/31	Risk Assessment Workshop
PH4/32	Impact of Impurities on CO_2 Capture, Transport & Storage
PH4/33	Improvement in Power Generation with Post Combustion Capture of CO_2
PH4/34	International Test Network for CO_2 Capture: Report on 7th Workshop
PH4/35	Overview of Long Term Framework for CO_2 Capture and Storage
PH4/36	Use of the Clean Development Mechanism for CO_2 Capture and Storage
PH4/37	Modelling of Ocean Storage of CO_2 – The GOSAC Study