CO_2 Capture Project

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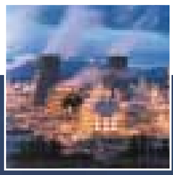

project results

Co-operating for a better environment

CO_2 Capture Project

The CO_2 Capture Project (CCP) is a partnership of government and industry that is supporting research to advance the scientific and technical basis for the capture and geological storage of CO_2. This will provide a new set of options for reducing CO_2 emissions that can complement improved energy efficiency and increased use of non-fossil energy resources.

Sponsors of the CO_2 Capture Project:

Government

European Union
US Department of Energy
Norwegian Research Council KLIMATEK Programme

Industry

BP
ChevronTexaco
EnCana
ENI
Norsk Hydro ASA
Shell
Statoil
Suncor Energy Inc.

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Co-operating for a better environment

www.co2captureproject.org

Introduction

The prospect of climate change is a matter of deep public concern. There is an increasing consensus that appropriate action to mitigate climate change will mean stabilising the concentration of CO_2 in the Earth's atmosphere. There are many technology options that can help, but it is clear that all may add additional cost to the price we pay for energy.

Given the scale of the climate challenge and the need to provide affordable energy in many different cultural, social and operational settings, a portfolio of approaches will be required. The solution will not be the same in every setting. One option that has broad potential application is the technology of CO_2 capture and geological storage. Capturing and storing the CO_2 from the combustion of coal, oil and natural gas could deliver material reductions in emissions and provide a bridge to a lower carbon energy future.

That is why the participants of the CO_2 Capture Project (CCP) decided to work together and collaborate with governments, industry, academic institutions and environmental interest groups, to develop technologies that will reduce the cost of CO_2 capture and demonstrate that underground, or geological storage is safe and secure. The goal is to reduce the impact of fossil fuel based energy production and use - at a time when global energy demand is growing faster than ever - all at an affordable cost.

Industry and government jointly fund the project, and the technology research and development is carried out by a wide range of academic and commercial institutions, all subject to open and comprehensive peer review. The views of external groups, such as Non Governmental Organisations (NGOs), are also being incorporated. Through international public-private collaboration of this kind, we believe the CO_2 Capture Project can make a real difference; co-operating for a better environment.

Gardiner Hill
Manager, Environmental Technology Programme, BP
Chairman, CCP Executive Board

An external viewpoint...

There are many ways to reduce CO_2 emissions. Our focus should be to minimise energy use by improving energy efficiency. At the same time, we should move as quickly as possible towards renewable energy sources such as solar and wind.

If CO_2 capture and storage is pursued to complement rather than to compete with efficiency and renewables, a number of NGOs feel it could play a useful interim role in reducing CO_2 emissions. In particular, it may have the potential to help blunt emissions from the hundreds of coal and gas-fired power stations that will be built over the next few decades, especially in fast developing economies like China. It could also help facilitate a bridge to a future hydrogen economy based on renewables by stimulating investment in the necessary infrastructure. But the technology is at a relatively early stage of development and there are long-term economic, safety and regulatory concerns that need to be addressed.

Only by carefully considering the issues and working together can we hope to successfully address the problem of CO_2 emissions. By actively engaging with environmental interest groups like Climate Action Network Europe, the CO_2 Capture Project is pursuing research into carbon capture and storage that is mindful of our concerns, and is sharing information that helps us better understand the technologies and their potential.

Jason Anderson
Climate Action Network Europe

Climate Action Network Europe co-ordinates the climate policy activities of environmental NGOs at European Union level

Climate Change

The nature of CO_2

Carbon dioxide, or CO_2, is a colourless, odourless gas that exists in the atmosphere at trace concentrations. Although invisible, it is fundamental to life on earth - plants use CO_2 in photosynthesis and return CO_2 to the environment when they decay. Carbon is also emitted from volcanoes, dissolved in the oceans, and bound in minerals. All of these factors affect the level of CO_2 in the atmosphere.

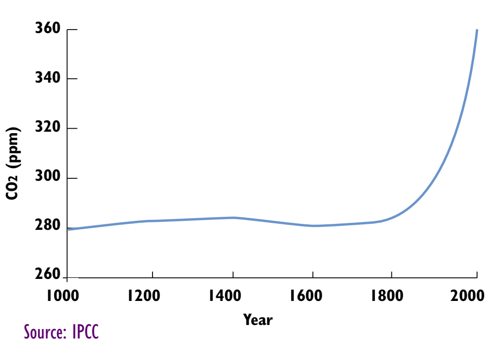
Along with other gases, CO_2 plays an important role in regulating the Earth's climate, letting sunlight pass through the atmosphere to warm the planet, but hindering the escape of heat. This is known as the greenhouse effect, without which the Earth's average temperature would be a chilly -18 degrees Celsius.

CO_2 and climate change

Since the Industrial Revolution, humans have altered the pace of the carbon cycle by extracting and burning fossil fuels (oil, gas and coal) and by replacing forests with farmland. These actions have released billions of tonnes of CO_2.

Ice cores and other lines of evidence tell us that since 1750, there has been a 30% increase in the amount of CO_2 in the atmosphere, from about 280 to 370 parts per million (ppm).
Evidence also shows that past increases in atmospheric CO_2 were associated with climatic warming. Since the 19th century there has been a 0.5 degrees Celsius rise in global average temperature and there is a consensus view that this is largely due to rising CO_2 levels caused by burning fossil fuels.

Global atmospheric concentration of CO_2



Source: IPCC

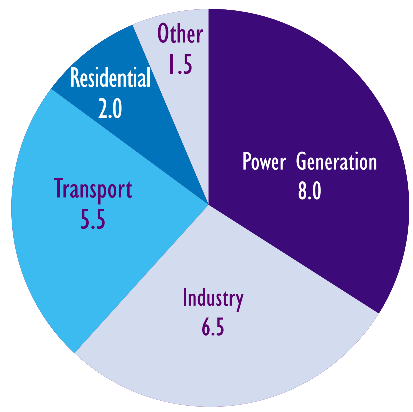
At our current pace, CO_2 is expected to reach double the pre-industrial level by the end of this century. At the same time, the Earth's temperature is expected to rise by 1.4 to 5.8 degrees Celsius, a rate of change that appears to be unprecedented in the last 10,000 years.

Although the effects of this warming would vary with geography, it is predicted to lead to increased threats to human health from disease and extreme climate events. Agriculture and ecosystems would likely be adversely affected in many regions. Precipitation patterns may change. Water shortages may become more serious in water-scarce regions, and low-lying coastal regions would face increased risks of flooding. The combined economic and social impacts of these changes could be large, particularly for developing countries.

Stabilising CO_2 levels

To avoid the predicted consequences of climate change, it is necessary to stop the atmospheric level of CO_2 rising. But because the climate system takes time to equilibrate, CO_2 concentrations will continue to rise for a time even as emissions are decreased. If emissions were held at current levels for the next 50 years, for example, society would be on track to stabilise at a concentration of 500 ppm (versus 370 ppm today).

The chart below is a summary of the main sources of CO_2 emissions from fossil fuel combustion.



Sources of CO_2 emissions from fossil fuel combustion (billions of tonnes of CO_2 per year)
Source: International Energy Agency (IEA) 2003

Given the increasing demand for energy, particularly in rapidly developing economies, the International Energy Agency predicts that CO_2 emissions from these sources will increase by around 70% by 2030. Coal-fired electricity generation for example is set to double during this timeframe.

If we are to work towards the stabilisation of CO_2 emissions, then strategies need to be found that will supply the additional energy required without releasing more carbon to the atmosphere.

The options include renewable energy (e.g. solar, wind and biofuels) switching to cleaner fuels (e.g. from coal to natural gas), nuclear energy, increased energy efficiency and CO_2 capture and storage. It is clear that no one strategy will be sufficient to tackle the problem. A portfolio approach will be required.

General Overview CO_2 Capture & Storage

What is CO_2 capture and geological storage?

The idea is to capture CO_2 from large industrial sources, before it is emitted to atmosphere, and to store it deep underground in secure geological formations, where it would be trapped indefinitely. If applied to some of the world's major CO_2 emissions sources, such as coal and gas-fired power stations and other major industrial facilities, this could reduce atmospheric emissions of CO_2 by millions of tonnes per year.

Experience and understanding of CO_2 in both industrial and natural settings is the basis for confidence in the feasibility of capture and storage schemes. CO_2 is found naturally in geological formations around the world, where it is trapped in much the same way as other fluids, such as oil and natural gas. It is also a familiar industrial commodity with a wide range of uses, from the carbonation of drinks to refrigeration, cooling and food preservation, pH control, welding, chemicals manufacturing and enhanced oil recovery.

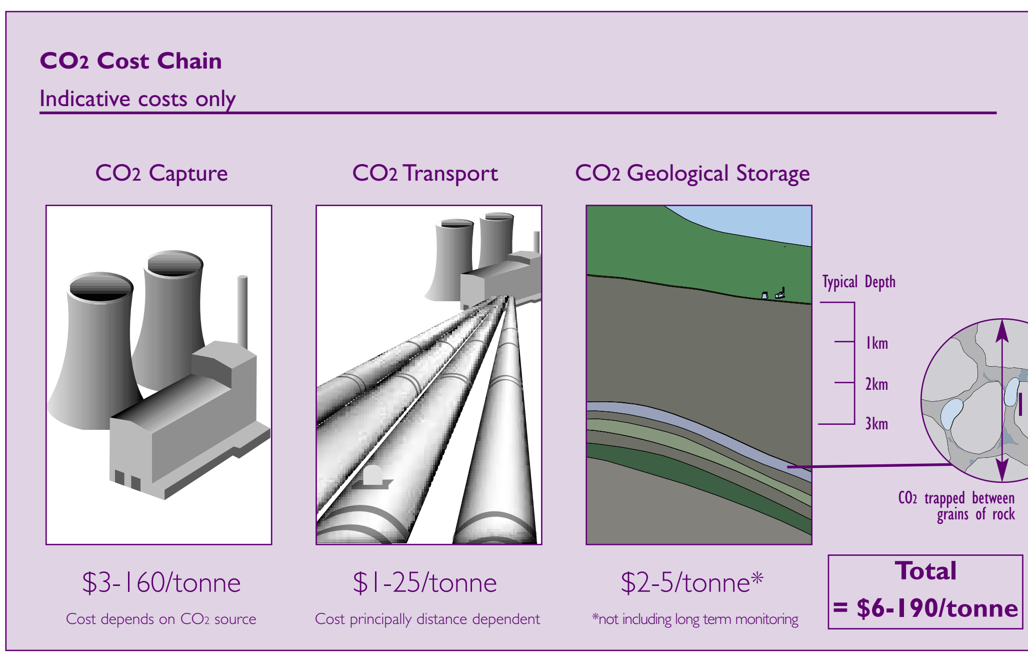
Much of the technology used in these industries could be adapted for capture and storage. But technical know-how is only part of the story. The CCP has identified the key issues that need to be addressed before CO_2 capture and storage can be widespread.

Cost

Today, the technology to capture and store CO_2 is expensive. The table below shows CCP research-based estimates for each stage of the process. The most expensive - the separation and capture of CO_2 in the first place – varies according to the source (please see CCP baseline calculations for four real life emissions scenarios on page 6). Implementation of individual CO_2 capture and storage schemes will depend on assessment of the cost versus benefit compared with other climate change mitigation options and on the financial incentives that are put in place to reduce greenhouse emissions, for example through emissions trading schemes. In the meantime, the development of advanced, lower cost technologies increases the scope of potential application.

Public Acceptance

The acceptance of capture and storage as a viable climate change mitigation option depends on the level of confidence in the ability of geological reservoirs to trap CO_2 for long periods of time, as well as a clear understanding of the benefits and risks involved. Appropriate regulations also need to be developed in order to establish and enforce appropriate standards and responsibilities for the implementation of capture and storage schemes.



The CO_2 Capture Project

In the first phase of the project, a wide range of technical studies were selected to complement other research programmes underway around the world. The overall aim was to advance the scientific basis for capture and storage and expand the potential scope of implementation.

CCP objectives

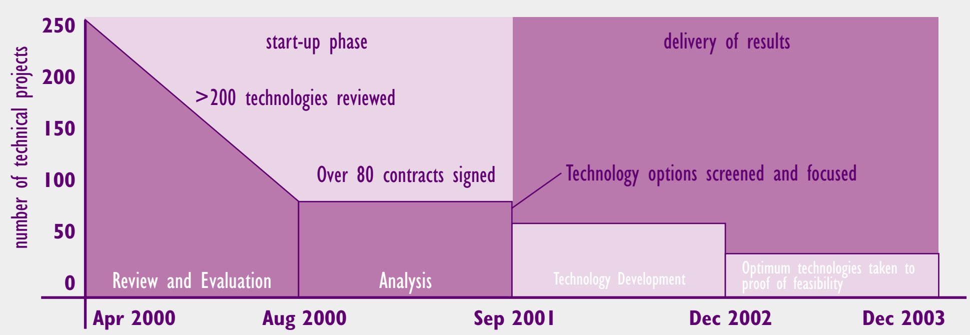
1. To identify and develop technologies to reduce the cost of CO_2 capture by 50%-75%.
2. To identify best practices and reduce uncertainties associated with geological storage of CO_2.

CCP cash contributions

Funding / $ millions	8 companies	3 governments	total
Economic modelling	0.5	0.5	1.0
Post-combustion capture	1.5	1.5	3.0
Oxyfuel capture	1.0	1.0	2.0
Pre-combustion capture	4.0	4.0	8.0
Storage, monitoring and verification	4.0	4.0	8.0
Technical Sub-total	**11.0**	**11.0**	**22.0**
Non-technical	3.0		3.0
Total	**14.0**	**11.0**	**25.0**

All numbers rounded to nearest $500,000

CCP Timeline



Research contracts

Over 200 projects were initially evaluated and at the end of 2001, over 80 contracts were signed with a range of national, academic and commercial institutions. The project teams have been managed and co-ordinated by technology experts from each of the eight funding companies. A full list of CCP research projects can be found on pages 18 & 19.

Peer review

At key decision points, CCP projects and decisions were peer reviewed by a Technology Advisory Board (TAB) comprising independent experts from industry and academia as well as representatives from the three funding governments. The TAB provided challenge to the project teams, advice on external benchmarking and peer review and assurance that the best technical practices were employed in delivery of the project.

External engagement

NGO focus group meetings were held in 2002 and 2003, providing an opportunity for the CCP to share interim results and for open dialogue between industry, government and environmental interest groups from Europe and America.

NGO Participants at 2003 Focus Meeting:

- Natural Resources Defence Council (NRDC)
- Climate Action Network Europe (CANe)
- Keystone Centre
- Pew Centre
- Bellona Foundation

Technical papers

Technical papers have been delivered at several industry conferences, notably the International Energy Association's (IEA) Sixth Greenhouse Gas Technology conference (GHGT-6) in Kyoto, Japan. At the time of publication, submissions are being prepared for the Seventh Greenhouse Gas Technology conference (GHGT-7) in 2004.

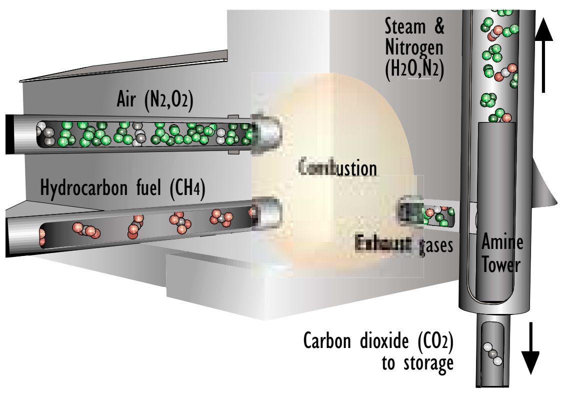
CO_2 Capture General Overview

CO_2 has been captured from both natural and industrial sources for many years. The challenge for wide scale application is to reduce costs and to develop technologies that can be applied to the world's largest CO_2 sources, ranging from coal and gas-fired power stations to oil refineries, chemical plants and iron and steel production facilities. The three main techniques for CO_2 capture are outlined below.

Diagrams representing 3 methods of CO_2 capture applied to a gas-fired power station.

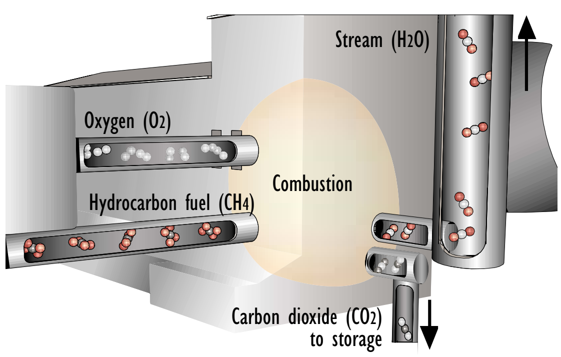
Post-combustion capture

CO_2 can be captured from the exhaust gas after a fuel is burned, using solvents such as amines, in a process known as absorption. The CO_2 is absorbed by the amines at particular temperatures and pressures and can be removed by varying the temperature and pressure.



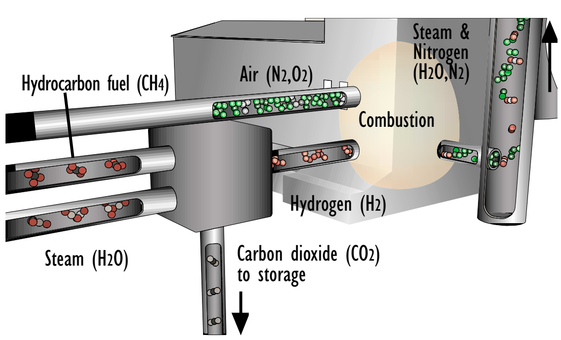
Oxyfuel capture

Fossil fuels can be burned in pure oxygen rather than in air. This results in a higher combustion temperature and when CO_2 capture is not required it is inherently more expensive, but when CO_2 capture is required, it gives the advantage of an exhaust stream composed almost exclusively of CO_2 and steam. The CO_2 can be captured simply and cheaply by condensing the steam.



Pre-combustion capture

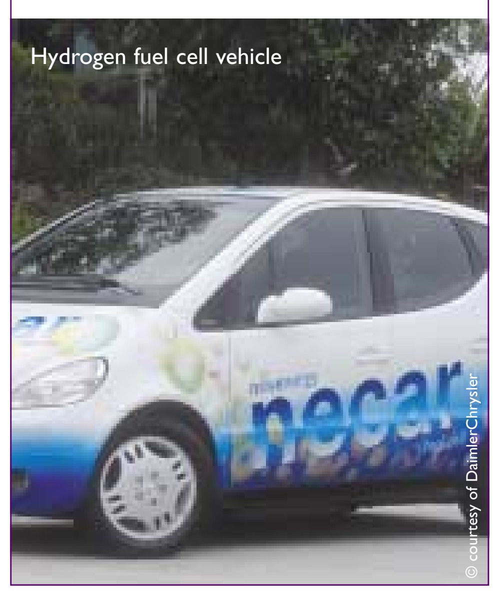
The pre-combustion capture process is based on two main steps; first, the conversion of a fossil fuel into a mixture containing hydrogen and CO_2 (known as syngas) and second the separation of the CO_2, leaving the hydrogen to be used as a clean fuel. The combustion of hydrogen produces no CO_2 emissions and the main by-product is water.



CO_2 capture and storage and the hydrogen economy

Hydrogen is often cited as a fuel of the future in everything from transport to home heating to large scale electricity production. Whilst the advantages and disadvantages are still being debated, the key benefit is that combustion of hydrogen produces virtually no Greenhouse Gas (GHG) emissions. The main by-product is water. It is one of the few fuels that could substitute for oil in the transport sector, which is forecast to account for the highest proportion of the expected growth in energy demand over the next twenty years.

Hydrogen can be produced by the electrolysis of water using renewable energy, such as solar or wind power, but the cost is currently prohibitively high for wide scale application. One potential advantage of pre-combustion capture is the opportunity to produce large quantities of hydrogen cost effectively from fossil fuels. Combined with geological storage of the CO_2, this could offer a low cost, zero emissions pathway towards the introduction of hydrogen as a fuel, stimulating investment in key infrastructure and reducing overall CO_2 emissions in advance of large scale renewables-based hydrogen production.



Hydrogen fuel cell vehicle

CO_2 Capture Project Results

Grangemouth refinery - 1 of the 4 CCP emissions scenarios

Research team focus

The CCP set up research teams to examine each of the three methods of CO_2 capture (post-combustion, oxyfuel and pre-combustion) and each team was led by experts from the eight funding companies. The primary focus was to identify and develop a range of practices and technologies that could reduce the cost of CO_2 capture and would be suitable for a wide scale implementation, including coal, oil and natural gas based applications.

Cost reduction objective

The ambitious nature of the CCP's cost reduction target - to identify technologies that could reduce the cost of CO_2 capture by 50-75% - reflects the fact that for CO_2 capture and storage to play a significant role in reducing emissions over the next few decades, a lot needs to be done in a short space of time, especially when compared to the usual pace of technology development. It is important to note however that any cost reduction achieved effectively expands the potential scope of capture and storage schemes.

Emissions scenarios and common economic model

In order to facilitate the development of technologies that would be suitable for a range of emissions sources, the CCP's capture programme was based around four real-life emissions scenarios. Two of the scenarios (an oil refinery and distributed gas-fired power generation turbines) were existing facilities, requiring the retrofitting of capture technologies, whilst the other two (a gas-fired power station and coke gasification scheme) were new-builds, where CO_2 capture could be incorporated from the planning stage.

In each case, the first step was to establish the total cost of CO_2 capture using the best currently available technology, providing a baseline against which the new techniques could be compared. This was done using the Common Economic Model (CEM), developed specifically by the CCP to calculate the total costs of different capture technologies in different settings. The model uses standardised input and material costs in order to allow direct and meaningful comparison of one technology to another as well as taking into account the total energy requirements of building and maintaining the capture facilities to give an overall cost (in $ per tonne) of CO_2 avoided for each technology.

CCP Emissions Scenarios

Scenario	Fuel source	CO_2 source	Retrofit / new build	Uncontrolled emissions/million tonnes CO_2 per year	Baseline capture cost* / $ per tonne CO_2 avoided
Distributed gas turbine power generation, Alaska	Natural gas	Small distributed turbines	Retrofit	2.6	$88/tonne
Grangemouth refinery, UK	Hydrocarbon gas & liquids	Heaters & boilers	Retrofit	2.6	$78/tonne
Gas-fired power station, Norway	Natural gas	Large electric power generation turbines (CCGT)	New build	1.3	$62/tonne
Coke gasification scheme, Canada	Solid gasification (petroleum coke)	Steam, H_2, & electricity cogeneration	New build	4.9	$15/tonne

*using current best available technology

CO_2 Capture Project Results

The post-combustion research programme

The post-combustion team was charged with evaluation of existing technologies that may be useful at the large scale required for capture and storage as well as to stimulate new technology development. The studies included detailed analysis of the best currently available technology (used for the baseline calculations for the four scenarios) to identify all cost-reduction opportunities. This work was done in two stages, first to reduce costs for a stand-alone separation plant and second to investigate the integration of the separation plant with the power plant. Other research groups identified and tested the advanced solvents that could be used for post-combustion capture. Better adsorbents, new chemical approaches and alternative equipment technologies were also investigated. Finally, the post-combustion team defined what is referred to as BIT (Best Integrated Technology), based on a combination of the studied technologies.

Key findings

- Changes to the design and integration of current technologies could significantly reduce the cost of post-combustion capture and would be applicable at large scale. Testing is required to confirm the viability and cost-reduction potential.
- The combination of two established technologies – the MHI KS-1 solvent and the Kvaerner membrane contactor – offers the potential to reduce energy consumption, and hence operating cost, for the post-combustion process.
- The combination of simplified design standards and advanced solvents / membrane contactors in a Best Integrated Technology (BIT) case could reduce the cost of the overall CO_2 capture process by around 50% although more work is required to test these processes. It is considered that this advanced, lower cost technology could be commercially introduced before the end of this decade with ongoing development work.
- Some novel chemical and process ideas for post-combustion capture have been developed, with the potential to deliver significant cost reductions, although more work needs to be done before the cost reduction potential can be properly assessed.

The oxyfuel research programme

The oxyfuel team looked at the potential cost savings that combustion using pure oxygen (known as oxyfiring) may give compared to conventional combustion in air. The goal was to establish a 'baseline' for oxyfuel capture using existing technology as well as to research new techniques. One key aspect of the work was to investigate the adaptation of current boilers, heaters and turbines to cope with the higher combustion temperatures that result from oxyfiring - either by redesigning key components or by reducing the temperature by recycling some of the CO_2 from the exhaust gas and pumping it back into the combustion chamber (known as exhaust gas recycling). Other studies focused on techniques to reduce the cost of separating oxygen from air in the first place - such as oxygen transfer membranes (known as ionic transport membranes) and chemical looping (transferring oxygen to the fuel by means of a metal oxide acting as an oxygen carrier).

Key findings

- Exhaust gas recycling is an extremely promising near term option that can be retrofitted to existing heaters and boilers. It could also be combined with state-of-the-art air separation techniques to reduce CO_2 capture costs even further.
- The conversion of gas turbines to oxyfiring has high potential but is a longer term proposition.
- The development of boilers, heaters and turbines that can operate at high temperatures would pave the way for further cost reductions but requires new metallurgy and is a longer term prospect.
- The chemical looping and ion transport membrane studies have shown some highly promising results and could significantly reduce the cost of separating oxygen from air, although further research and development is required in both cases.

The pre-combustion research programme

The CCP pre-combustion team looked at the integration of existing technologies into one complete process as well as the development of advanced techniques for steam reforming and hydrogen separation, including selective hydrogen transport membranes and new adsorbent materials that could be used in a reaction known as 'sorbent-enhanced water gas shift'.

Key findings

- Pre-combustion capture technologies can be applied to all fossil fuel sources and offer the opportunity to reduce the cost of CO_2 capture for all four of the CCP scenarios.
- Sorption enhanced water gas shift and membrane enhanced water gas shift technologies offer considerable cost-reduction opportunities.
- An advanced hydrogen membrane reformer system, developed for the Norwegian gas-fired power station scenario, shows the highest cost reduction potential for any CCP capture technology, although considerable additional testing is required.

CO_2 Capture Project Results

Conclusion

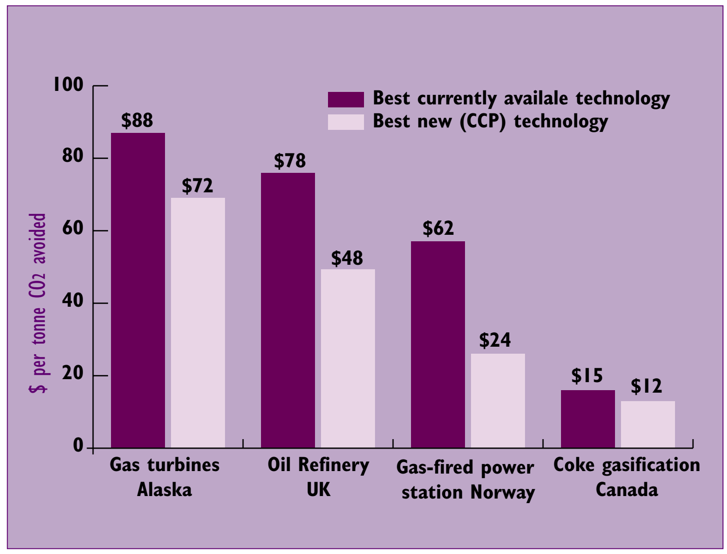
Once the capture technologies being developed by the CCP had been taken to proof of concept stage, the most promising were subjected to a more detailed cost assessment. The results have shown significant potential savings for all scenarios, ranging from 16% for the coke gasification scheme to 60% for the gas-fired power station.

Whilst different technologies are at different stages of development, the wide range identified by the CCP means that they could be suitable for many of the world's major emissions sources. Techniques developed for gas-fired power generation for example could also be used for coal-fired power generation, if combined with the gasification of coal.

Pre-combustion capture, where some of the most significant advances have been made, is applicable to all fossil fuel sources and may also offer the opportunity to produce large amounts of hydrogen cost-effectively, helping to stimulate the development of a hydrogen based energy economy in the future.

With continued public-private partnership, the next step will be to work towards the commercial scale demonstration of the most promising technologies developed by the CCP as well as the achievement of further cost reductions. This is helping to bring forward the day when society could benefit from cleaner energy from fossil fuels.

Potential cost savings of best CO_2 Capture Technologies



Potential cost savings of CCP Capture Technologies

	Alaska distributed gas-fired power generation	UK oil refinery	Norway natural gas power station	Canada coke gasification
Baseline cost (best currently available technology) $ per tonne of CO_2 avoided	$88.2	$78.1	$61.6	$14.5
CCP developed technologies cost / $ per tonne of CO_2 avoided (% variation from baseline)				
Pre-combustion capture technology				
Membrane water gas shift (GRACE & DOE-membrane)		$48.1 (-38%)		
Membrane water gas shift (GRACE & Pd-membrane)		$52.4 (-33%)		
Sorption enhanced water gas shift	$71.8 (-19%)			
Sorption enhanced water gas shift - O2ATR			$42.7 (-31%)	
Sorption enhanced water gas shift - AirATR			$34.4 (-44%)	
Very large scale auto thermal reformer	$76.0 (-14%)			
Hydrogen membrane reformer			$24.4 (-60%)	
Advanced coke gasification				$12.2 (-16%)
Post-combustion capture technology				
Nexant integrated baseline design			$35.1 (-43%)	
MHI solvent (KS1) with Kvaerner membrane			$47.5 (-23%)	
Best integrated technology (Nexant BL integrated & MHI-KS1)			$28.2 (-54%)	
Oxyfuel capture technology				
Oxyfiring with flue gas recycle & ionic transport membranes (ITM)		$41.0 (-48%)		
Oxyfiring with flue gas recycle & ASU		$48.7 (-38%)		

Cost reductions determined using Common Economic Model with generic (US Gulf Coast) material costs and standardised energy prices

CO_2 Storage General Overview

Photograph of sandstone reservoir rock (magnified 15x)

Geological storage involves compressing the CO_2 captured from industrial sources and injecting it into suitable rock formations, typically thousands of metres below the Earth's surface, where it would be trapped indefinitely.

Possible sites for CO_2 storage occur all around the world. Two of the main options are producing or depleted oil and gas fields. These have the advantages that the geology is generally well understood and they are proven traps, having held fluids (often including CO_2) at high pressure for millions of years. CO_2 is already injected into some oil fields to increase oil production (please see text box on page 10 entitled 'relevant industry experience') and in some cases, the infrastructure built up to recover the oil or gas (e.g. injection wells, pipeline transportation networks) could be adapted to put CO_2 back into the reservoir.

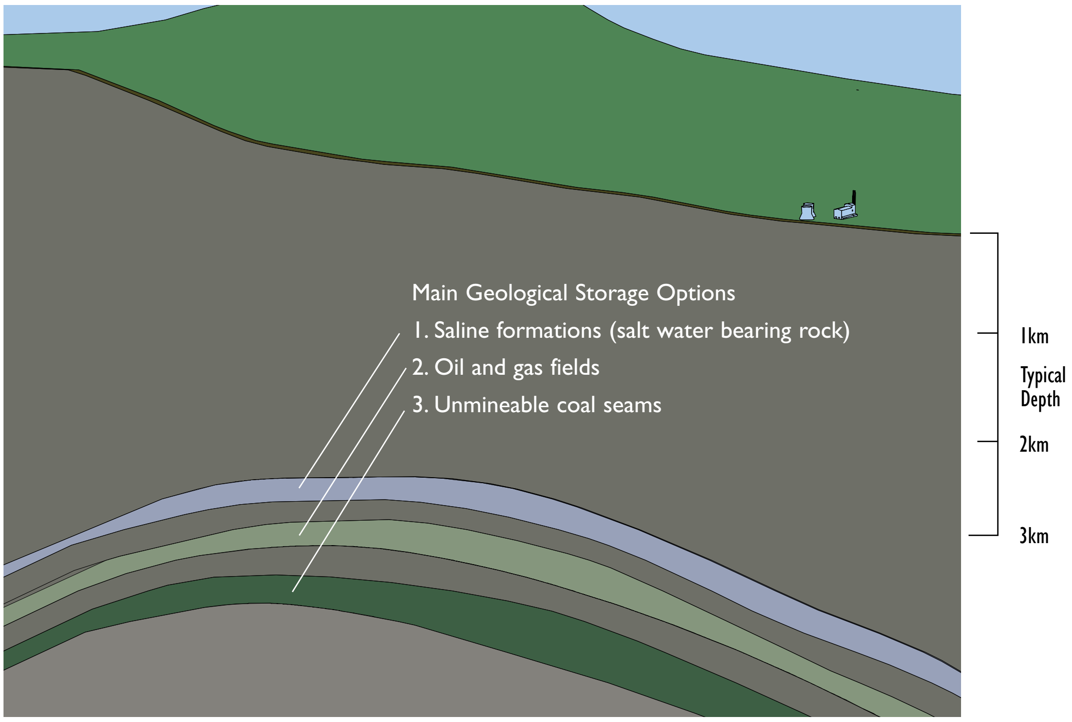
Other storage options include unmineable coal seams (where the CO_2 would be adsorbed onto the coal) and deep salt water bearing rock formations, also known as saline formations.

The CCP has looked at all of these storage options although the research has focused principally on producing and depleted oil and gas fields and deep saline formations as these are considered to have the greatest global storage potential (see 'estimated storage capacity' table below). CO_2 would be trapped in permeable rocks (i.e. sandstones), capped by impermeable rocks (i.e. shales).

Estimated Storage Capacity

Storage option	Global capacity	
	Gt CO_2	% emissions to 2050
Depleted oil and gas fields	920	45
Deep saline reservoirs	400-10,000	20-500

Source: IEA Greenhouse Gas R&D Programme



CO_2 Storage General Overview

Relevant industry experience

The practice of CO_2 storage is underpinned by the experience and technology built up by the industries that handle fluids, such as oil, natural gas and CO_2, on a daily basis. A wide range of modern day practices can be employed, from the laboratory analysis of rocks to assess the storage potential of individual reservoirs, to time-lapse 3D seismic surveys to track the movement of CO_2 underground.

One important area of expertise is the use of CO_2 for enhanced oil recovery (EOR). In many parts of the world, CO_2 is injected into producing oil fields, where it pushes oil towards the production wells. Practices for the safe handling, transportation and injection of CO_2 are well established and, while most of the CO_2 is currently recycled, some schemes might be adapted to trap CO_2 permanently in the reservoir. This is a promising near term option as the cost of implementing the storage scheme would be partially offset by additional oil production.

Natural gas storage is another key area of experience. Natural gas is currently stored in geological formations, including those suitable for CO_2 storage, such as saline formations and depleted gas fields, to help deal with variations in demand at different times of the year. Many of the practices employed by the industry, including injection, monitoring and remediation techniques, would also be applicable for CO_2 storage.

Based on the experience and understanding of industries like these, a number of CO_2 storage demonstration projects are already underway. The Weyburn project in Canada is combining EOR with CO_2 storage, whilst in the Norwegian North Sea, Statoil is storing around one million tonnes of CO_2 per year in a deep saline formation. In the Algerian desert, the In Salah gas project is being set up to store CO_2 in a gas field.

Key issues

Notwithstanding the current level of knowledge and experience that can be applied to CO_2 storage, the CCP has identified a number of key issues that need to be addressed before the practice can be widespread.

Identifying appropriate storage sites

The ideal storage reservoir would be one in which CO_2 can be trapped permanently in place and where the risk and potential impact of leakage is minimised. Selecting the most appropriate sites requires a detailed understanding of different geological formations and the behaviour of CO_2 within these formations, including the factors that lead to permanent trapping of CO_2 and the features that could lead to leaks to the surface.

Responding to leaks

It is important to understand the likelihood of CO_2 leakage from different storage sites and the potential impact on ecosystems close by, as well as to have remediation strategies in place to address the causes and consequences of leaks. It is also important to establish an 'acceptable' rate or level of leakage, above which remediation plans would be acted upon. The issue of CO_2 leaks will be key to public acceptance of CO_2 storage.

Monitoring

Once injected into a reservoir, the movement of CO_2 will need to be monitored, both to assess the ongoing integrity of storage and to identify the nature and rate of any leaks. The challenge is to identify and develop cost effective techniques that have the appropriate resolution and that can be maintained over long periods of time.

Handling, transporting and injecting CO_2

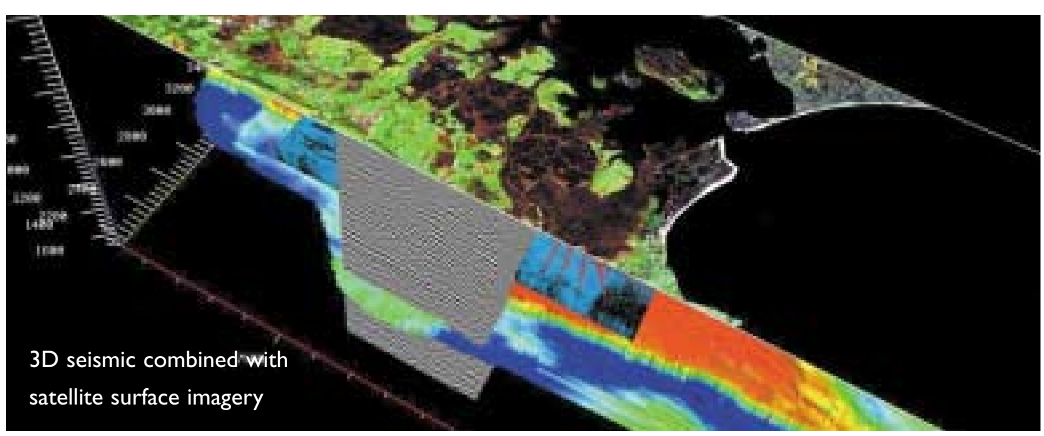
CO_2 is already transported by ship and pipeline for many industrial applications. The challenge is to identify the most efficient and appropriate techniques for transportation and injection, especially considering the scale of the infrastructure that would be required in order to make a significant difference to world CO_2 emissions.

Cost

The implementation of CO_2 storage schemes will depend on an assessment of the whole-life costs of individual projects compared to other climate change mitigation techniques as well as on the mechanisms put in place to offset the cost of emissions reduction, such as emission trading schemes.

Policies and regulations

Policies and regulations are required at a global and national level in order to establish consistent standards for geological storage. An appropriate monitoring and verification framework is also needed to achieve wide scale recognition and crediting. For example, the European Union's Emissions Trading Scheme's monitoring and verification guidelines do not yet have any provision for CO_2 capture and storage. In general, there is little policy development specific to capture and storage, although several countries are now moving in that direction. Furthermore, international conventions that may have a bearing on geological storage, such as the London Convention and the OSPAR Convention, need to be clarified before widespread implementation can take place and may at present discourage the deployment of CO_2 capture and storage schemes.



3D seismic combined with satellite surface imagery

CO_2 Storage Project Results

The CCP's storage programme should be viewed in the context of the wider body of work underway around the world. Having surveyed the portfolio of projects sponsored by other agencies, such as the EU, US and Australian governments, the CCP identified key issues that were not addressed elsewhere and that were considered important in order to make CO_2 storage a practical reality.

The work was organised into four key areas (see below) and 30 technical studies were commissioned with the overall objective of reducing uncertainties and identifying best practices for geological CO_2 storage.

The Storage Programme Structure

Integrity - Assessing the competence of natural and engineered systems to contain CO_2 (The research in this area fed into the risk assessment work).

Optimisation - Improving the efficiency and economics of transporting and storing CO_2.

Monitoring - Developing techniques to track CO_2 movements in and beyond the storage reservoir.

Risk assessment - Developing a formalised framework to quantify and minimise the probability and impact of CO_2 leakage from storage sites.

Integrity

Geological systems are complex and thus vary widely in their suitability for long-term CO_2 storage. Engineered systems such as wells, although necessary for operation of CO_2 storage facilities, introduce additional vulnerability to CO_2 leakage. The CCP "integrity" studies addressed issues related to the natural and engineered features of geological reservoirs.

Key findings

- Analysis of why naturally occurring CO_2 accumulations do or do not leak highlights which features (e.g. reservoir and cap rock geometry, lithology) are amenable to secure CO_2 storage.
- Simulations of physical and chemical interactions of CO_2 with reservoirs (minerals) and fluids (oil, gas, water) show that CO_2 is trapped (immobilised) by a variety of methods:
  - Buoyancy of the CO_2 phase relative to reservoir water results in upward migration where CO_2 is trapped by cap rock.
  - Solubility trapping (where CO_2 dissolves into the water in the reservoir) is effective depending on salinity and reservoir conditions.
  - Pore space trapping of CO_2 via capillary forces is recognised as a major trapping mechanism.
  - Mineralisation of CO_2 to form carbonates is a relatively minor, long-term trapping mechanism.
- Two independent reservoir simulations show that much of the injected CO_2 would be effectively trapped over a hundred-year time frame and most over a thousand-year time frame. Different completion and injection strategies can be used to maximise CO_2 trapping.
- Experimental work and modelling of the geochemical and geomechanical effects of CO_2 injection on reservoir and cap rocks can be used to establish safe rates and capacity of CO_2 injection. 3D effective stress analyses can be used to predict activation of faults due to CO_2 injection.
- The integrity of engineered systems, particularly wells, was identified as a particular vulnerability in CO_2 storage. There is a need to develop resistant materials for use in new wells and remediation techniques for old wells. Nevertheless, even in a worst case scenario of well failure, most CO_2 would remain in the reservoir for at least 100 years, allowing time for well remediation.

Optimisation

The optimisation program sought to take advantage of processes used by other industries to efficiently transport, inject and manage gases. Potential economic offsets to CO_2 storage costs in the form of enhanced oil and gas recovery, or use of existing infrastructure, were also addressed.

Key findings

- Adapting enhanced oil recovery (EOR) schemes may offer some of the earliest opportunities to implement CO_2 storage projects while recovering some or all of the costs associated with CO_2 capture, transportation and storage facility management. Key issues that need to be addressed include the applicability of the EOR industry experience (mostly in West Texas) to more diverse reservoir types and identifying the economic trade-offs between oil production and ultimate CO_2 storage.
- CO_2 storage in depleted gas fields (with or without enhanced recovery) offers the advantages of existing transport and injection infrastructure as well as proven gas containment. The CO_2 capacity of gas reservoirs may be up to 5 times that of the original hydrocarbons due to the high compressibility of CO_2.
- The natural gas storage industry, with its extensive European and North American installations operating safely for decades, offers a viable analog to CO_2 storage. Site assessment criteria, leakage paths and some intervention strategies are available for application to CO_2 storage.
- The economic feasibility of some CO_2 storage projects will depend on the extent to which conventional carbon steel can be used in long distance pipelines. Experimental and theoretical studies indicate that existing, stringent hydration specifications to avoid corrosion might be relaxed under some circumstances.
- Impurities such as SO_x and NO_x left in post-capture CO_2 streams (for the sake of economy) may have a deleterious effect on surface equipment (compressors, pipes etc.) but appear unlikely to affect CO_2 storage performance or effectiveness of CO_2 EOR.

CO_2 Storage Project Results

Monitoring

The CCP's monitoring studies evaluated the applicability and cost-effectiveness of a broad range of technologies from various vantage points, including subsurface imaging of CO_2 movement and surface / atmospheric monitoring of CO_2 leakage. Selection of the appropriate monitoring program will depend on site-specific factors and the monitoring timeframe envisioned.

Key findings

- Storage sites can be monitored from a variety of perspectives, from subsurface geophysical imaging of CO_2 movement to remote (satellite / aerial) detection of diffuse and point source leakage.
- Remote surveys (e.g. geobotanical hyperspectral) can detect CO_2 leakage to the surface indirectly by identifying resultant changes in plant life and mineral assemblages. Adaptation of the instrumentation to direct detection of CO_2 might provide better resolution and broader applicability.
- Conventional geophysical techniques such as time-lapse (4D) seismic have been demonstrated as effective in monitoring CO_2 movement in the subsurface in some settings. Lower resolution techniques such as gravity, electromagnetics and streaming potential, however, may offer adequate alternatives and lower costs.
- Natural and introduced tracers such as noble gases offer a sensitive, cost effective means of monitoring CO_2 migration paths in the reservoir as well as leakage out of the reservoir.
- Ground-based laser spectrometry techniques, properly configured with respect to the anticipated type (diffuse versus point source) and magnitude of leaks, are cost effective, well established monitoring techniques.

Risk assessment

Risk assessment applied to geological storage of CO_2 is relatively new although the general principals have been applied in other industries. The CCP risk assessment studies range from characterising the leakage vulnerability of individual geological and engineered features to holistic "systems" approaches that predict how these features will interact in a given local setting. For the risk assessment process to be acceptable to regulators and the public it has to be conducted logically and transparently with active engagement of stakeholders.

Key findings

- An initial survey study put into perspective the hazards associated with CO_2 handling relative to that of other industrial materials. The physical and chemical characteristics of CO_2 are well understood from a health, safety and environment perspective and a regulatory framework for its use is available.
- A study on early detection, intervention and remediation of CO_2 leakage outlines possible scenarios and impacts as well as identifying technologies that might be used in response.
- Simulation of CO_2 movement to the near surface (vadose zone) and into the atmosphere predicts CO_2 dissipation patterns for different leakage rates and volumes (flux) at given localities.
- Two comprehensive risk assessment methodologies were developed. Each allows for the identification of risk factors for leakage and a quantifiable assessment of likelihood and consequences of occurrence. Preliminary testing has been conducted on a North Sea aquifer model and a Colorado coal bed. The former showed no leakage over a 10,000-year timeframe, and the latter showed how specific practices (e.g. well placement) can be used to avoid CO_2 leakage.
- Subsurface microbial ecosystem changes induced by CO_2 injection warrant attention because of potential production problems arising from mineral dissolution and gas generation.
- The next logical step in risk assessment includes standardisation of FEPs (features, events and processes) and formal benchmarking with methodologies developed by other organisations.

Conclusion

One of the main achievements of the CCP has been to view potential geological storage sites as holistic systems and to introduce a new, risk-based approach that takes into account all of the factors that could influence the integrity of storage as well as the likely consequences of CO_2 leaks. The next step will be to test and refine the risk assessment methodologies in the field but, if proven, they could offer a sound scientific basis for site selection, as well as identifying the most appropriate monitoring and remediation strategies.
In addition to this, the modelling work funded by the CCP is increasing understanding of how CO_2 is trapped underground and increasing confidence in the long-term storage ability of geological reservoirs.

Other studies are helping to identify the best techniques for transport and injection of CO_2 as well as for cost effective, long-term monitoring. Optimising the processes and materials involved in geological storage brings forward the day when it could be commercially applied.

By funding and co-ordinating a range of research projects like these, the CCP is helping to confirm the potential of geological storage and to build the scientific and technical basis for implementation. In the next phase, the focus will be on the integrity of well bores (which pass through the geological formations), further development of the assurance processes (monitoring, verification and risk assessment) and to work towards field demonstrations of the most promising techniques.

With the continued co-operation of governments, industry, academia and environmental interest groups, the CCP could help to establish a new economic, regulatory and technical basis for the wide scale implementation of geological storage schemes, helping to significantly reduce CO_2 emissions to atmosphere.

Project Conclusion and Next Steps

There are many factors that impact the world's energy mix, including social and economic development, security of supply, local environmental impact and global climate change. Optimising the balance between these factors means that energy is likely to come from a wide range of sources in the future.

Given the increasing demand for affordable energy, particularly in fast developing economies like China and India, the International Energy Agency predicts that fossil fuels will continue to dominate energy supply for many years to come.

In order to tackle climate change, the impact of fossil fuels must be reduced, and whilst improving energy efficiency will help, it will not be enough on its own. For this reason, CO_2 capture and storage is firmly on the international agenda.

The governments, companies and research organisations involved in the CCP have identified technologies that could halve the cost of CO_2 capture and are advancing the scientific and technical basis for long-term geological storage.

This is helping to establish CO_2 capture and storage as a viable climate change mitigation option, one that could complement the development of new energy sources, contribute to material reductions in CO_2 emissions and meet the needs of societies around the world. It may also provide a low-cost, zero emissions pathway to the hydrogen economy.

Ultimately, implementation will depend on confidence in the capacity of geological reservoirs to store CO_2 as well as the policies and incentives that are put in place to address the issue of climate change. But, with the potential to minimise emissions from some of the largest CO_2 sources in the world, CO_2 capture and geological storage could become a key part of our response to climate change.

More work is needed before CO_2 capture and storage is applied on a wide scale and the CCP plans to address the key issues in their next phase. The proposed programme themes are outlined here.

CCP phase 2 (2004-07): program themes

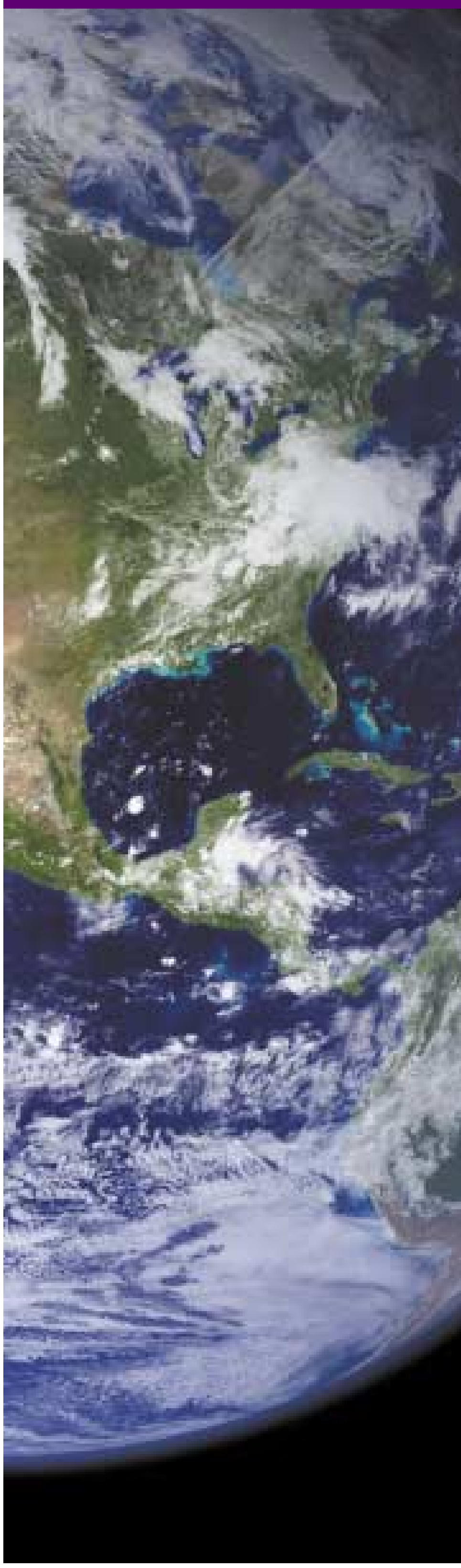
Capture Technology
- Continued cost reduction
- Further development of short-listed technologies
- Focus on current and new technologies
- Pilot scale demonstration of a capture technology - possibly via strategic partnerships

Storage Technology
- Assurance (monitoring, verification & risk assessment)
- Well integrity
- Demonstration projects - possibly via strategic partnerships

Industry Standards and Public Acceptance
- Protocol / industry standards for capture & storage
- Stakeholder outreach and education
- Business environment for CO_2 Capture & Storage

Networking
- Crosscutting and sharing

List of research programmes



Post-Combustion Capture Programme

Provider	Contract	Co-Funder
Fluor Limited	CCP Baseline Study	CCP
Kvaerner	Electric Swing Adsorption (ESA)	CCP
Norsk Hydro	Channel Concept Preliminary Study	CCP
Oakridge National Lab (UT Battelle)	Post Combustion ESA & Carbon Fiber Composite Molecular Sieve (CFCMS) Study	DOE
SRI (Stanford)	Radical Chemistry (Self Assembled Nano-porous Materials for CO_2 Capture)	DOE
Kvaerner	Amine Scrubbing/Membrane Contactor	NORCAP
MHI	Amine Scrubbing/Membrane Contactor	NORCAP
Nexant	Cost Efficient Design & Integration	NORCAP
Norsk Hydro	Radical Chemical Concepts	NORCAP

Pre-Combustion Capture Programme

Provider	Contract	Co-Funder
Foster Wheeler	Advanced Syngas Study	CCP
Haldor Topsoe	Pre-combustion Membrane Reactor	CCP
Jacobs Engineering	Very Large Scale Autothermal Reforming (VLS ATR)	CCP
Air Products	Compact Reformer Membrane Contactor	DOE
Air Products & Chemicals, Inc.	Sorption Enhanced Shift Reaction (SEER/SEWGS)	DOE
ARI	Capture Study Integration and Reporting	DOE
Colorado School of Mines (CSM)	Sulfur Poisoning Resistant Palladium/Copper Alloy Composite Membranes	DOE
Davey	Compact Reformer Membrane Contactor	DOE
Eltron Research	Membrane Water Gas Shift (WGS) Reactor Development Study	DOE
Energy Resource Centre	Membrane WGS Reactor Dev. Study	DOE
Fluor Daniel	Gasification CO_2 Separation Development (Advanced)	DOE
Fluor Federal	Membrane WGS Reactor Development Study	DOE
General Electric (GE)	Gas Turbine Retrofit	DOE
SOFCo / McDermott Technology, Inc.	WGS Reactor Design, scale up and cost assessment	DOE
TDA Research, Inc.	WGS Sulfur Poisoning Resistant Palladium/Copper Alloy Composite Membranes	DOE
University of Cincinnati	Zeolite Membranes & Their Applications In Membrane Reactors For WGS Reaction	DOE
Institute for Membrane Technology	GRACE PCDC STUDIES Membrane Reformer	EU/GRACE
KTH	GRACE PCDC STUDIES	EU/GRACE
Norsk Hydro	GRACE PCDC STUDIES Hydrogen Membrane Technology	EU/GRACE
Sintef	GRACE PCDC STUDIES Investigation of High Temperature Hydrogen Membrane	EU/GRACE
Universidad de Zaragoza (UNIZAR)	GRACE PCDC STUDIES Use of Pd/Zeolite Composite Membranes	EU/GRACE
University of Twente-AMK	GRACE PCDC STUDIES Membrane Activities	EU/GRACE
Institute for Energy Technology (IFE)	Generation of H2 Fuels	NORCAP
Jacobs Engineering	Standardized PCDC	NORCAP
Norsk Hydro	Hydrogen Membrane Technology	NORCAP

Oxyfuel Capture Programme

Provider	Contract	Co-Funder
Air Products & Chemicals Ltd.	Oxyfuel boilers and heaters recycle	CCP
Alstom Power	Zero Recycle Oxyfuel Boiler Pre-Study	CCP
Mitsui Babcock	High Pressure Oxyfuel Boiler Study	CCP
Mitsui Babcock	Zero or Low Recycle Oxyfuel Boiler Study	CCP
Sintef	Oxyfuel Power Generator Cycles Study	CCP
Alstom Power Boilers (AV)	Chemical Looping Combustion Economics and Scale-up	EU/GRACE
Chalmers University of Technology	Chemical Looping Combustion (CLC)	EU/GRACE
Consejo Superior de Investigaciones	Particle Development, Screening & Comprehensive Testing	EU/GRACE
Vienna Uni of Technology	Chemical Looping Combustion Fluidisation Studies	EU/GRACE

Cost Estimation and Economics

Provider	Contract	Co-Funder
Edward S. Rubin	Common Economic Model (CEM) Study	CCP
Howard J. Herzog	CEM Study	CCP
Norsk Hydro	Cost Estimation (Nils Eldrup)	CCP
Telemark	CCP Cost Screening Cost Estimation	CCP
Fluor Inc.	Cost Evaluation of Selected Technologies	DOE
Praxair	Advanced Boiler Concept	DOE
Alstom	Azep Economic Evaluation	NORCAP
Cost Technology AS	2003 CCP Cost Screening Cost Estimation	NORCAP

List of research programmes

Storage Assurance Programme		
Provider	**Contract**	**Co-Funder**
Advanced Resources Int'l (ARI)	Natural CO_2 Field Analogs for Geological Sequestration	CCP
GFZ Potsdam	Influence of CO_2 Injection on Reservoir and Caprocks	CCP
Hy-Vista	Rangely Survey	CCP
IEA Greenhouse Gas Programme	Gas Storage Technology	CCP
IEA Greenhouse Gas Programme	Remediation & Early Warning Workshop / White Paper	CCP
Lawrence Berkeley National Lab	HSE Risk Assessment Literature Search, Synthesis of Findings with Roadmap	CCP
New Mexico Institute Mining Tech.	Leveraging EOR Studies	CCP
Serco Ltd.	Weyburn CO_2 Monitoring Project	CCP
Tang Associates (CalTech)	Atmospheric CO_2 Monitoring Systems	CCP
Various	SMV 2002 Workshops - Santa Cruz	CCP
APCRC	Geomechanical Effects of CO_2 Storage	DOE
ARI	SMV 2003 Workshops	DOE
Battelle	CO_2 Impurities Trade-off - Surface	DOE
Exchange Monitor	CCP 2004 Closeout Workshop	DOE
Geolas (Princeton)	Impact of CO_2 on Subsurface Microbes	DOE
Idaho National Lab (Idaho)	HSE Probabilistic Risk Assessment Methodology	DOE
Lawrence Berkeley National Lab	Investigation of Novel Geophysical Techniques for Monitoring of CO_2 Migration	DOE
Lawrence Berkeley National Lab	HSE Risk Assessment of Deep Geological Storage Sites	DOE
Lawrence Berkeley National Lab	SMV Study Integration & Reporting	DOE
Lawrence Berkeley National Lab	Remediation & Early Warning Workshop / White Paper	DOE
Livermore National Lab	Hyperspectral Geobotanical Remote Sensing for CO_2 Containment	DOE
Livermore National Lab	Noble Gas Isotopes for Screening and Monitoring Long Term Migration	DOE
Livermore National Lab	Reactive Transport Modelling to Predict Long-Term Cap-Rock Integrity	DOE
Monitor Scientific (Sci Monitor)	Top Level Synthesis of Nuclear Waste Disposal	DOE
TNO-NITG	Safety Assessment Methodology for CO_2 Sequestration	DOE
TNO-NITG	CO_2 Optimum Monitoring Methodology	DOE
ON Communication	Communication Consulting Services 2003/4	DOE
Penn State Uni.	Infrared Lasers to Detect CO_2 Leakage	DOE
Sintef	Long Term Sealing Capacity of Cemented Petroleum Well	DOE
Stanford University	Monitoring Aquifers & Reservoirs Using Satellite Radar Interferometry	DOE
Tang Associates (CalTech)	Estimation of Capability to Monitor For Leakages of CO_2	DOE
Texas Tech University	Use of Depleted Gas & Gas Condensate Reservoirs	DOE
Tie-Line Technology (Tie-Line)	Screening Tool of MMP/MME Evaluation	DOE
University of Texas	CO_2 Impurities Tradeoff - Subsurface	DOE
University of Texas (UTX)	SMV Simulation	DOE
Utah State University (Utah State)	Evaluation of Natural CO_2 Charged Systems as Analogs for Geological Sequestration	DOE
AEA Tech / ECL Tech	Optimization of Storage & Risk Assessment Methodology	EU/NGCAS
BP	Management, Risk Assessment, Monitoring & Mitigation	EU/NGCAS
British Geological Survey (BGS)	Methodology for Assessment of Storage Options	EU/NGCAS
Statoil	Technology Transfer	EU/NGCAS
GEUS	Basin Model Development	EU/NGCAS
IEA Greenhouse Gas Programme	Technology Transfer	EU/NGCAS
Institute Francais du Petrole (IFP)	Basin Modelling and Geochemistry	EU/NGCAS
ERM	ERM Policy & Incentives Team; Review	NORCAP
Gas Technology Institute (GTI)	Gas Storage Technology	NORCAP
Institute for Energy Technology (IFE)	Materials Selection For CO_2 Capture & Storage	NORCAP
Nansen Institute	Legal Aspects of CO_2 Underground Storage	NORCAP
ON Communication	Communication Consulting Services 2003/4	NORCAP
Reinertsen Engineering (Reinertsen)	Transportation Properties of CO_2	NORCAP

Acknowledgments

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Further information about the CO_2 Capture Project and the individual research projects can be found at the CCP website:

www.co2captureproject.org

Information about other CO_2 capture and storage projects can be found at the website of the International Energy Agency (IEA) Greenhouse Gas Programme:

www.co2sequestration.info

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CO_2 Capture Project