

Appendix

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A.1 Physical Properties of CO₂

Carbon dioxide (CO₂) is a colourless, odourless, tasteless gas, which is not flammable and – at the normal atmospheric concentration of approx. 0.04 vol.% – not toxic. With a specific gravity density of 1.85 kg/m³ (at 15 °C and 1 bar) it is about 1.5 times heavier than air and consequently accumulates in low areas when present at high concentrations. The highest permissible workplace concentration is 0.5 % or 5,000 ppm (parts per million). Because carbon dioxide displaces atmospheric oxygen, breathing air with concentrations greater than 7–8 % will lead to death by suffocation within 30 to 60 minutes.

As the phase diagram shows (Fig. A-1), CO₂ is a gas (g) under normal conditions (1.0 bar/15 °C) and freezes at a temperature of –78,5 °C (Table A-1). Frozen CO₂ is referred to as dry ice. Below 5.8 bar heating causes it to pass directly from the solid state (s) to the gaseous state (sublimation). The liquid phase (l) exists only above the triple point (TP) of 5.8 bar and –57 °C. The triple point is the point where all three phases coexist in equilibrium. So at ambient temperatures CO₂ can be compressed for example to 100 bar for transport purposes. In the liquid state the density increases (e.g. to 824 kg/m³ at 15 °C and 51 bar), meaning that in the liquid state the volume to be dealt with is much smaller than in the gaseous state. In the supercritical range (supercr.) above the critical point (CP) of 74 bar and 31 °C CO₂ occurs in a uniform phase with a constant density (464 kg/m³).

A.2 CO₂ Capture Methods (to Chapter 5)

Several fundamentally different methods are available for decarbonising combustible gases and flue gases. In the following we describe the methods and their characteristic features and assess their suitability for possible use in CO₂ sequestration systems.

Table A-1: Chemical and thermodynamic properties of carbon dioxide (CO₂)

Molecular weight	44.01	kg/kmol
Relative density of gas (air = 1)	1.53	–
Density of gas	1.85	kg/m ³
Density of liquid*)	(–50°C / 6.84 bar)	1,156 kg/m ³
	(0°C / 34.86 bar)	928.8 kg/m ³
	(15°C / 50.85 bar)	823.8 kg/m ³
	(31.06°C / 73.84 bar)	463.7 kg/m ³
Density of solid	≈ 1,550	kg/m ³
Boiling/freezing point (at 1 bar)	–78.5	°C
Triple point	5.81 bar	bar
	–56.6	°C
Critical point	73.84 bar	bar
	31.06	°C
*) Saturated		
Source: Dubbel (1990), Reiniger and Schubert (1999), Richter (2003)		

CO₂ capture methods can be placed in two basic categories:

- low-temperature methods and
- high-temperature methods.

With **low-temperature CO₂ capture methods** the gases generally have to be cooled and the water condensed out before the actual capture process begins. The low-temperature methods are:

- Chemical absorption in organic and inorganic solutions (alcohol-amine, alkali carbonate, etc.),
- Physical absorption in organic and inorganic solutions (methanol, propylene carbonate, water),

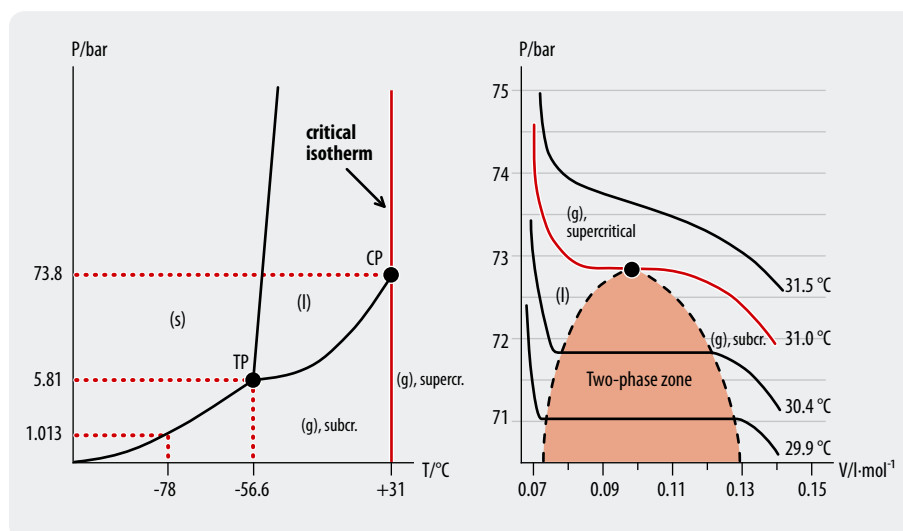


Fig. A-1: Phase diagrams for carbon dioxide (p/T diagram on left, p/V diagram on right) (Reiniger and Schubert 1999)

- Adsorption on solids (molecular sieves, activated carbon, etc.)
- Cryogenic distillation
- Membrane methods

Methods using **chemical and physical absorption** in solutions are current state of the art. Their suitability for CO₂ capture has been extensively demonstrated in gas scrubbing processes and enrichment. The most commonly used solutions are: ethanol amine (monoethanol, diethanol, triethanol amine), potassium carbonate, propylene carbonate, methanol (Rectisol), polyethylene glycol dimethyl ether (Selexol), and others. The most extensively tested process is capturing CO₂ from flue gases with monoethanolamine (MEA). For example, a CO₂ scrubber using a 20 % MEA solution has been operating since 1991 at a 300-MW CHP plant at Shady Point (Oklahoma). The daily production of 200 t of CO₂ is used in the food industry. Because amine is degraded by impurities such as dust, SO₂, NO and O₂, these must be removed from the flue gas before amine capture (Hendricks 1994).

Zeolite molecular sieves, activated carbon, aluminium oxide, silica gel, etc. can be used to capture CO₂ in **adsorption systems**. This technology is state of the art, but has not yet been used in the power station sector. The most commonly used process is pressure swing adsorption (PSA) with molecular sieves. One major drawback of molecular sieves is their affinity for water. Consequently any water must be condensed out before CO₂ capture.

CO₂ can be condensed out of gas mixtures through cooling at pressures as low as 4–5 bar (**cryogenic distillation**). Exxon has developed and industrially tested the controlled freezing zone process. The process is energy-intensive, especially when the CO₂ concentration is low. However, its advantage is that capture and compression for transport are accomplished in a single step. Today it is already used for conditioning biogas, but no experience has yet been gathered in the power station sector.

Membrane methods separate gases by making use of differences in their ability to pass through thin membranes. Efficient separation demands high selectivity, a large membrane surface and high permeability for the desired gas components. This method is currently under development and is not yet state of the art. Today membranes are used for gas separation on a small scale. They are especially efficient for separating gases with very different-sized molecules. Membrane separation of H₂ is today close to becoming competitive with other methods. By contrast, given the still very poor membrane selectivity, CO₂ capture from flue gases (largely N₂/CO₂ mixtures) is still a long way from commercial application, and no breakthrough can be expected in the next ten to fifteen years.

High-temperature methods for CO₂ capture are based on binding CO₂ to oxides or silicates, e.g. CaO. This method is still at the development stage. Its attraction is that CO₂ capture occurs at high temperatures, so (tar-

laden) combustible gases from a gasification process can pass to a turbine without having to be cooled first. This allows efficiency to be increased in comparison with conventional CO₂ capture methods (e.g. scrubbing). It makes sense to implement these systems in IGCC power stations (coal-fired integrated gasification combined cycle) and gas-fired combined cycle power stations before combustion or directly in the combustion chamber. CO₂ bonding occurs at temperatures below the equilibrium temperature. The absorbent has to be regenerated after the absorption phase. The regeneration temperature is approx. 50–100 °C above the equilibrium temperature.

In the following section the aforementioned methods are briefly outlined and assessed. The theoretical specific energy requirement for the capture methods listed below relates to capture of CO₂ from flue gases (ZSW 1996). A distinction must be made between thermal and electrical energy. In practice the values are (sometimes) much higher so they should be treated with caution. The decisive factor is the achieved power station efficiency.

A.2.1 Chemical/Physical Absorption

Description of process: Chemical and physical absorption of CO₂ in solutions is an industrially tested capture method. In chemical absorption CO₂ is bonded chemically to organic or inorganic molecules. In physical absorption the amount of CO₂ the solvent will accept stands in an approximately linear relationship to the partial pressure of the CO₂. The levels of bonding energy involved are much weaker than with chemical absorption, which is advantageous when it comes to regeneration. After the CO₂ has been scrubbed from the raw gas the saturated solution must be regenerated and the CO₂ extracted. With chemical absorption the solutions are regenerated by heating, with physical absorption by a drop in pressure.

Theoretical specific energy requirement after ZSW (1996)

Chemical absorption:

1.08 MJ/kg CO₂ (MEA with 50 % capture rate)

1.95 MJ/kg CO₂ (MEA with 90 % capture rate)

Physical absorption: 0.1MJ/kg CO₂

Achievable capture rate:

Chemical absorption: 90 %

Physical absorption: 60–80 %

Applications and experience: The technology is state of the art. Whether physical or chemical scrubbing is used depends on the partial pressure of the CO₂. Below 10 bar chemical absorption is used, above 10 bar physical absorption.

Possible uses: CO₂ capture from flue gases (coal-fired thermal power stations, CC, coal-fired IGCC), e.g. at

Shady Point, Oklahoma (200 t CO₂/day for the food industry, ABB technology).

Advantages and disadvantages, CO₂ avoidance costs, power station efficiency: The operating temperature for chemical absorption is around 50–60 °C (for physical absorption less) so the gas being treated must be cooled and cleaned (of SO_x, NO_x, dust, etc.). This leads to loss of energy in the form of sensible heat. The power station technology must be adapted for absorption with solvents (e.g. gas scrubbing, O₂ concentration). Specific investment costs, e.g. for a CC power station, rise by about 87–93 % and the overall efficiency of the arrangement is – at about 48–55 % – significantly lower than without CO₂ capture. The CO₂ avoidance costs lie in the range of \$32–49/t CO₂. For a coal-fired power station the overall efficiency of 33–37 % is significantly lower than with a conventional generating process without flue gas decarbonisation. The specific investment costs rise by about 80 %. Specific CO₂ avoidance costs in the range of \$47–49 per avoided tonne of CO₂ are cited in the literature. One advantage of this method is that power stations can be retrofitted.

Technical limits and required R&D: Most solvents (especially amines) are subject to degradation over time, leading to losses and consequent environmental impacts (amines are toxic!). Degradation of the solvent depends strongly on the concentrations of impurities in the flue gases (e.g. SO_x and NO_x). Many solvents are also corrosive and consequently cause material problems. Research is still required into the development of corrosion-resistant materials. The system as a whole (power station plus CO₂ capture) has yet to be demonstrated in the long term.

Timeframe for large-scale application: The technology is available and is already used in the oil industry and for extracting CO₂ from power station waste gases for use in the food industry. Long-term experience in large-scale commercial power stations is still lacking.

A.2.2 Adsorption on Solids

Description of process: Zeolite molecular sieves, activated carbon, aluminium oxide, etc. can be used to capture CO₂ in adsorption systems. The most commonly used process is pressure swing adsorption (PSA) with molecular sieves. Adsorption is accomplished through physical forces (van der Waals forces). The adsorption phase is followed by regeneration by means of pressure reduction. The adsorbent can also be regenerated thermally (temperature swing adsorption) or in a combined process of pressure and temperature swing adsorption (PTSA). Molecular sieves have the highest CO₂ adsorption capacity per kg in comparison with other materials.

Specific energy requirement after ZSW (1996): 2.9 MJ/kg CO₂ (molecular sieves, PSA, TSA)

Achievable capture rate: 90 %

Applications and experience: The method is state of the art. So far it has only been used for small gas flows. No experience has yet been gathered in the use of this method with large gas flows (e.g. power stations).

Advantages and disadvantages, CO₂ avoidance costs, power station efficiency: Adsorption is a relatively simple, well-tested method, but it has not yet been used for large gas flows. The large energy requirement reduces the attractiveness of this method for CO₂ capture in power stations. Additional investment costs are not especially high. Energy consumption is lowest with PSA (approx. 1/3 compared with TSA). One important drawback is the affinity of molecular sieves for water. For this reason the water must be condensed out before CO₂ capture. Calculations show that in almost all types of power station, implementing CO₂ capture with PSA would double electricity generating costs.

Technical limits and required R&D: The process is mature, but not relevant for CO₂ capture in power stations. However, new methods such as metal oxide gels could make the process more viable.

Timeframe for large-scale application: The technology is already available, but unattractive for power stations. New advances could be ready for implementation in about twenty years.

A.2.3 Cryogenic Distillation

Description of process: CO₂ can be condensed out of gas mixtures by cooling at pressures as low as 4–5 bar. The gas mixture being treated must be dried first.

Specific energy requirement after ZSW (1996): 4.35 MJ/kg CO₂

Achievable capture rate: 90 %

Applications and experience: The method is very energy-intensive, especially where the CO₂ concentration in the gas is low. In the past it was used to extract CO₂ from gases with CO₂ concentrations > 90 vol.%. Today cryogenic distillation is already used for conditioning biogas (CO₂ + CH₄), but no experience has yet been gathered in the generation sector. Future implementation of the process would be conceivable with IGCC (O₂) and oxyfuel processes. However, from the energy (and consequently ecological) perspective application is very questionable.

Advantages and disadvantages, CO₂ avoidance costs, power station efficiency: The gas being treated must be free of water (big disadvantage). The method is only feasible for gas flows with high CO₂ concentrations. However, the advantage of this process is that capture and compression for transport are accomplished in a single step, with a single-stage process producing solid or liquid CO₂. Large-scale industrial application is not on the horizon. Calculations for IGCC and oxyfuel power stations show that cryogenic CO₂ capture would reduce

power station efficiency by 14 and 18 percentage points respectively. Investment costs increase by approx. 80 %. Another possibly more attractive application could arise with fuel-cell power stations, where CO₂ occurs in a very concentrated form.

Technical limits and required R&D: There is still a great need for research to optimise the process with the goal of significantly reducing the energy requirement.

Timeframe for large-scale application: The technology is in principle already available. Oxyfuel power stations and SOFC are regarded as the best opportunities for implementation. But commercial viability is not expected for another fifteen to twenty years.

A.2.4 Membrane Method

Description of process: Membrane methods make use of the different rates at which gases pass through thin membranes. Efficient separation demands high selectivity, a large membrane surface and high permeability for the required gas components in comparison with the other gases in the mixture. Polymers, metals or ceramics can be used as the membrane material.

Specific energy requirement after ZSW (1996): 1.15 MJ/kg CO₂

Achievable capture rate: 60 %

Applications and experience: CO₂ capture using membranes could be implemented with CC (reforming or combustion in O₂) and coal-fired IGCC power stations before or after combustion. However, membrane technology is not yet state of the art.

Advantages and disadvantages, CO₂ avoidance costs, power station efficiency: When used for CO₂ capture with CC or IGCC oxyfuel power stations (in situ CO₂ capture before combustion) the efficiency of the CC power station is 48–50 %, or 8–10 percentage points less than that of a conventional power station. The efficiency of a coal-fired IGCC power station with membrane capture is 35–39 %, or 6–10 percentage points less than IGCC without CO₂ capture. The specific investment costs are 33–54 % higher than for IGCC without CO₂ capture. The CO₂ avoidance costs are in the range \$18–40/t.

Technical limits and required R&D:

Development work is still required on the following components and processes:

- efficient membranes for separating CO₂
- reactor concepts for in situ CO₂ capture with high-temperature membranes
- high-temperature membranes for separating off O₂
- reactors for the separation process
- turbines for H₂-rich gases

Timeframe for large-scale application: The method is not state of the art but in the development stages. It will be available in ten to fifteen years at the earliest. Improvements are needed above all in selectivity, permeability and stability (at high temperatures). A combination of membrane and absorption solution would be an interesting prospect. This development is at the laboratory stage.

A.2.5 High-temperature Methods

Description of process: The high-temperature methods for capturing CO₂ are based on in-situ bonding of CO₂ (combustion, gasification, reforming) with oxides (quick lime, dolomite, etc.), silicates, etc. This method is still at the development stage. The attraction of the method is that CO₂ capture is accomplished at high temperatures so the combustion gases can pass to the turbine without cooling. This makes it possible to achieve higher levels of efficiency than with conventional CO₂ capture methods (e.g. absorption solutions). The CO₂ absorbent is located either directly in the conversion reactor (combustion, reforming, gasification, etc.) or downstream (e.g. in a shift reactor).

Specific energy requirement: 0.8 MJ/kg CO₂

Achievable capture rate: > 90 %

Applications and experience: High-temperature O₂ capture could be implemented in the pre-combustion phase in CC (steam reforming) and IGCC processes and in the combustion phase in coal-fired power stations. High-temperature absorbers for CO₂ are in the development stages. The promising options include natural carbonates (e.g. limestone and dolomite) and natural and synthetic silicates and zirconates. The most important property of the high-temperature absorber is its cyclic stability. For industrial application the absorbers must be able to withstand as many CO₂ absorption/regeneration cycles as possible without significant loss of capacity. Toshiba has developed a lithium orthosilicate that is claimed to maintain its stability over more than five hundred cycles.

Advantages and disadvantages, CO₂ avoidance costs, power station efficiency: The attraction of CO₂ capture at high temperatures is that the combustion gases do not need to be cooled, and can be used directly. In this case even tars in the product gas can be utilised without problems. CO₂ absorption is exothermic and the heat of reaction can be integrated in the process. One disadvantage of the process is the regeneration of the saturated absorbent, for which temperature change is the principal option. Repeated absorption/regeneration destroys the structure of the absorber, which gradually loses its capacity to absorb CO₂. The presence of water accelerates this process.

These materials have not to date been used industrially for CO₂ capture.

Technical limits and required R&D: Development work is still required on the following materials and process design:

- cyclically stable materials that withstand as many absorption/desorption cycles as possible without significant changes in absorption capacity
- reactor and process concepts for in situ CO₂ capture
- efficient regeneration.

Timeframe for large-scale application: The method is not yet available. Possible industrial application in approximately fifteen to twenty years.

A.2.6 Conclusions

As things stand today, the most efficient processes for CO₂ capture in power stations causes efficiency losses of 6–14 percentage points. In order to maintain the same nominal output the power stations consume approx. 15–35 % more fuel, and investment costs rise by 30–120 %. Capturing CO₂ from flue gases by absorption in solutions is state of the art and can be implemented in all (existing and future) power station types. Of all the CO₂ capture options, flue gas decarbonisation in conventional coal-fired power stations using absorption solutions is the least favourable.

There is believed to be great potential in pre-combustion CO₂ capture methods when combined with new power station types such as:

- CC with steam reforming
- IGCC
- Power stations using the oxyfuel process (combustion in O₂/CO₂).

This would require R&D in the fields of membranes for CO₂ and O₂, hydrogen turbines, power station engineering and high-temperature absorbers. Large-scale industrial application can be expected in approx. fifteen to twenty years.

Cryogenic distillation can be implemented where CO₂ occurs in concentrations upwards of 90 %, for example in oxyfuel power stations, high-temperature fuel cells (SOFC), chemical looping, etc. This would require development work in power station design. Large-scale industrial application can be expected in approx. fifteen to twenty years.

An economically advantageous solution is offered by pre-combustion capture of CO₂ in IGCC power stations. Commercial availability can be expected in fifteen to twenty years.

It should be noted that efficient methods of CO₂ capture are tied to power station technologies that are not yet state of the art. In the long term membrane technologies will play an important role in reducing the energy requirements and investment costs of CO₂ capture. A

combination of oxygen-permeable membranes and the oxyfuel process could in future lead to a major reduction in the energy required for CO₂ capture.

A.3 Worldwide Overview of CCS Projects (to Chapter 7)

Globally there are more than one hundred projects relating to CCS. A good overview and introduction is provided by the Intergovernmental Panel on Climate Change (IPCC):

www.ipcc.ch

and by two websites maintained by the International Energy Agency (IEA):

www.ieagreen.org.uk/ccs.html
www.co2captureandstorage.info.

The websites are organised by region and topic, making it easy to access the large amount of information. The world maps below show a selection of global activities in the fields of capture (Fig. A–2) and storage (Fig. A–3).

In international comparison North America has the most studies and projects relating to CCS (71), followed by Europe (36) and Asia (13) (as of October 2006). Japan plays an important role, running or participating in six of the Asian projects (see Table A–2, left-hand side).

If we look at the types of issue investigated (see Table A–2, right-hand side), CO₂ storage comes first with 44 studies addressing geological storage (30 of them in North America) and 8 (in the United States and Japan) examining marine storage options. In second place come 41 studies focusing on new technologies (especially in relation to the process of capture at the power

Table A–2: Global distribution of projects and main research areas (as of 10/06)

Number of projects by region		Number of projects by research area	
United States and Canada	71	Geological storage	44
Europe	37	New technologies	41
Asia (Japan)	13(6)	Uses for CO ₂	12
Australia	6	Modelling and databases	13
New Zealand	1	Marine storage options	8
Brazil	1	CCS costs	4
United Arab Emirates	1	CO ₂ monitoring projects	6
Algeria	1	Hydration	2
Total	131	CO ₂ transport	1
		Total	131

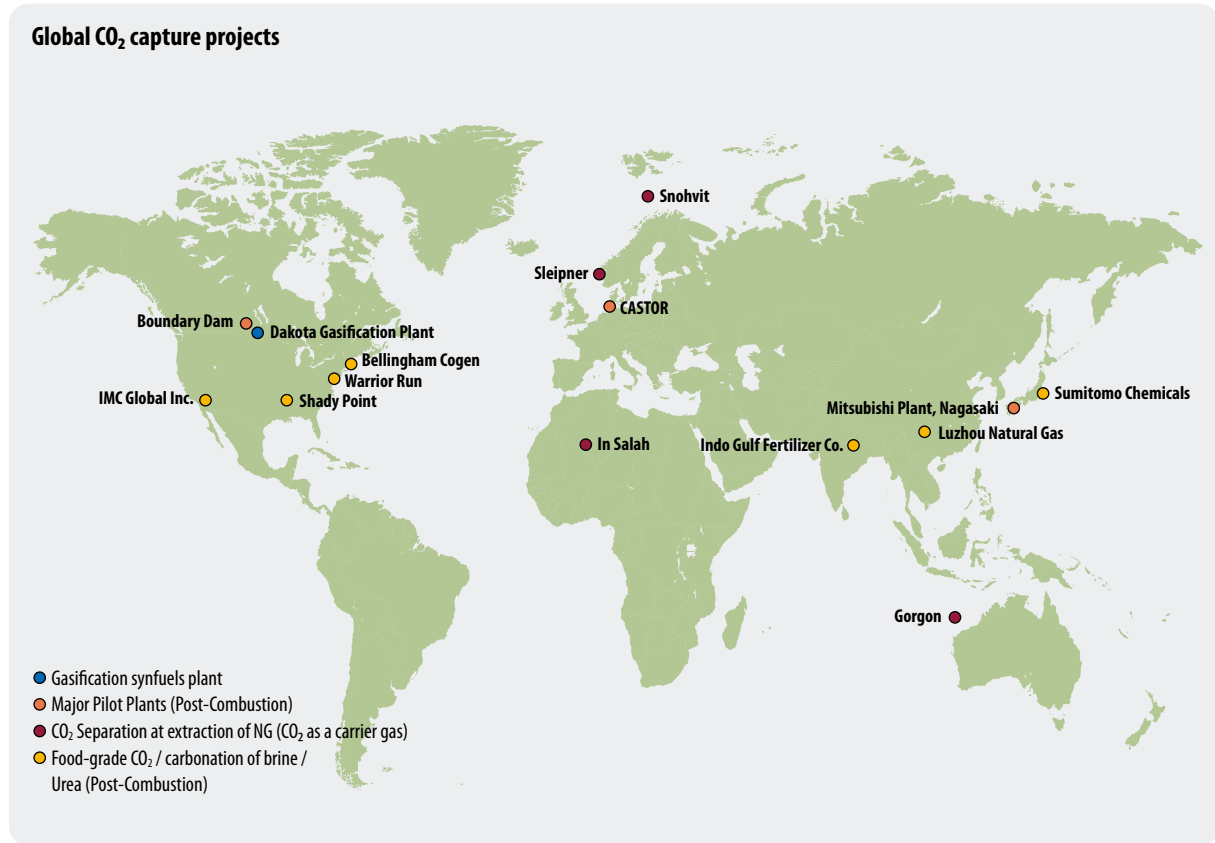


Fig. A–2: Global CO₂ capture projects (selection)



Fig. A–3: Selection of global CO₂ storage projects (<http://www.co2captureandstorage.info/docs/IEAGHGccsworldmap.pdf>)

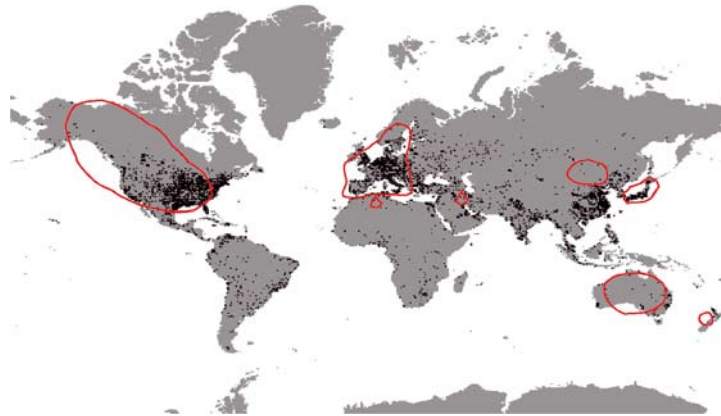


Fig. A–4: Overview of the global distribution of CCS projects (encircled in red) in relation to the major sources of CO₂ emissions (dots)

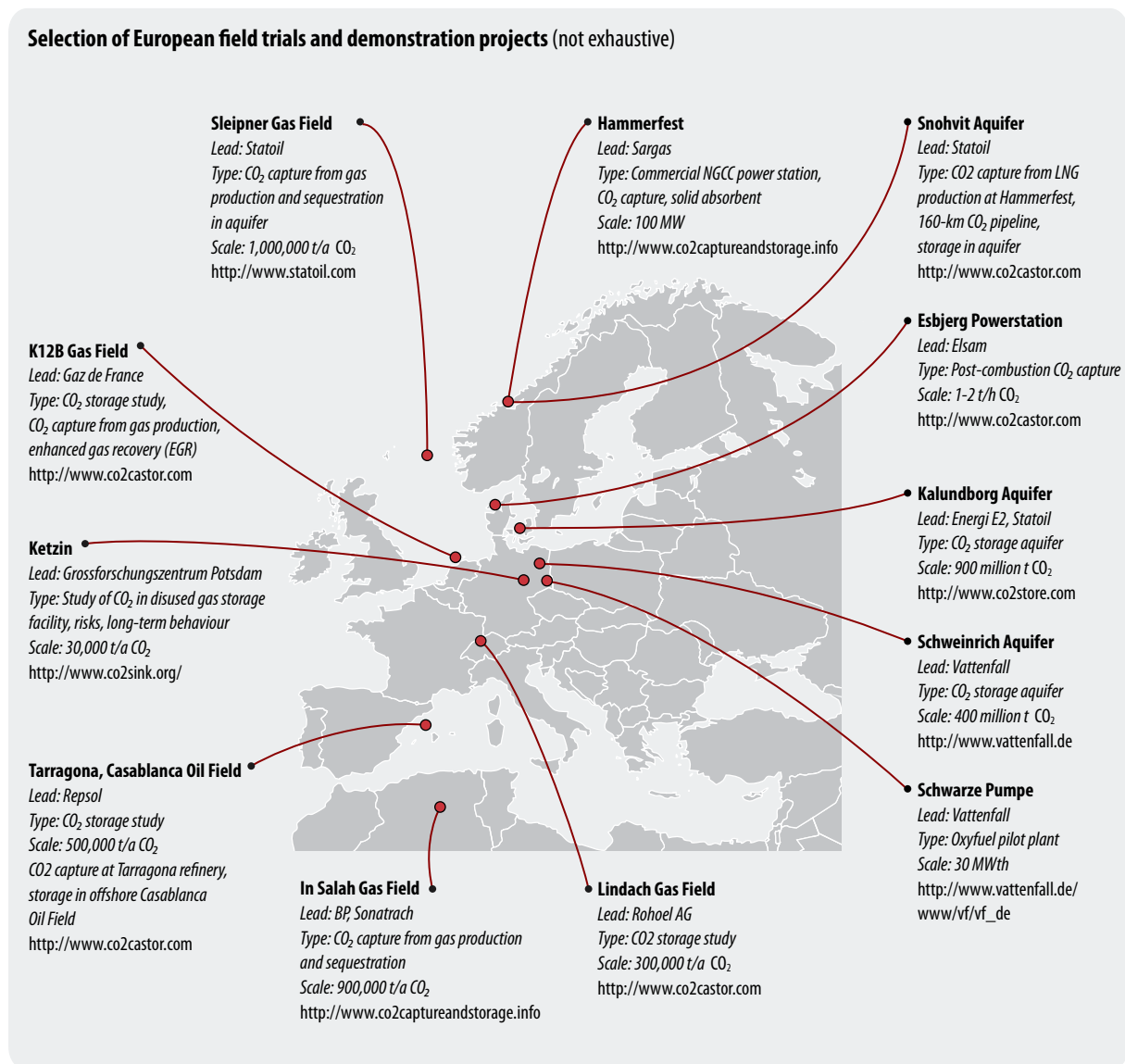


Fig. A–5: Selection of European field trials and demonstration projects (not exhaustive)

station) followed by 13 projects preparing models and databases and 12 on possibilities for using CO₂. One project analyses CO₂ transport and two involve hydration of CO₂,¹ while four projects focus on the costs of CCS and six investigate CO₂ monitoring.

A.3.1 Projects within the EU

The European approach to CO₂ reduction in the field of electricity generation from fossil fuels does not differ fundamentally from the activities worldwide. Generally priority is given to increasing power station efficiency, which reduces specific CO₂ emissions and in general also makes economic sense. Beyond this there are also numerous possibilities for CO₂ capture, as discussed below. The measures differ in terms of technology, cost of capture (e.g. energy consumption and financial cost), development status and thus availability timeframe. The development perspectives in different countries also differ according to the respective political and economic framework. As well as increasing efficiency, reducing the cost of capture processes is also another leading goal.

Fig. A-5 shows the distribution of field trials in Europe by way of illustrating the technological development perspectives. Most field trials already in existence or in advanced stages of planning tend to follow economic frameworks. As can be seen from the map (Fig. A-5) there is a concentration of field trials among the numerous oil and gas fields of the North Sea. On the one hand, locations are found where the CO₂ contained in raw natural gas has to be separated off when the gas is conditioned following extraction. On the other hand, project locations are also associated with the exploitation of oil fields, where CO₂ is injected to boost falling recovery rates (enhanced oil recovery or EOR). It is not yet clear to what extent the use of compressed CO₂ for EOR or EGR (enhanced gas recovery) can be regarded as a storage option.

There are considerably fewer field trials for CO₂ capture from power station flue gases or for developing new power station concepts with subsequent CO₂ transport and sequestration, because in these fields economic frameworks are not yet in sight. For one thing, CO₂ capture at the power station requires a great deal of energy (reduced efficiency, increased fuel consumption), while for another there is still a great shortage of information concerning long-term behaviour (leakage, environmental impact).

Through its research programmes the European Union promotes the development and demonstration of technologies and measures for reducing and storing CO₂. Activities concerning the field of energy are summarised at: http://europa.eu.int/comm/research/energy/nn/nn_rt/nn_rt_co/article_1150_en.htm.

There are national and international programmes for promoting CCS projects. In April 2005 the European Commission published the first draft of its seventh Research Framework Programme proposing a total of nine current research areas with a funding volume of €2,951 million for the period 2007–13. In the seventh Research Framework Programme – as was already the case in its predecessor – CO₂ capture and storage (‘near zero emission power generation’) plays an important role in the field of energy research, and in absolute terms has actually increased considerably in importance (see also http://europa.eu.int/comm/index_de.htm).

Furthermore, as part of its initiative to create a European Research Area (ERA) the European Commission supports the EU-level coordination of corresponding national programmes, for example in the field of low-emissions power stations the ERA Net FENCO (Fossil Energy Coalition). In December 2005 the EU also started a new technology platform on ‘CO₂-free’ power stations for fossil fuels.

The text box below outlines selected CCS research projects (in particular EU-funded projects) with information about their aims, timeframes and participating German research partners.

As well as the aforementioned research projects, **Sleipner** (Norway) and **CRUST** (Netherlands) represent two major European CO₂ storage projects that are already operating commercially.

In the field of research into CO₂ sequestration the following **networks** exist at the EU level:

CO₂GeoNet – This network focuses on geological CO₂ storage. The members come from the spheres of science and industry.

CO₂NET – The European networking development programme for geological CO₂ storage, CO₂ capture and zero-emissions technology has given rise to the European Carbon Dioxide Thematic Network (CO₂NET), which networks the geological agencies of EU member states and other research institutes.

EuroGeoSurveys – Network supporting the EU by collecting the entirety of technical know-how of the geological agencies of EU member states and membership candidates.

Eurogif – Represents the European oil and gas service and supply industry. ‘EUROGIF brings an industry perspective to the EU in terms of their formulation of both energy policy and Framework Programmes for sponsored research.’

¹ Process whereby water molecules become attached to dissolved ions through electrostatic forces between the charged ions and the water dipoles.

CASTOR: CO₂ from capture to storage
CO₂ storage in aquifers / CO₂ storage in hydrocarbon reservoirs / membranes / modelling and mapping / monitoring and verification / physical absorption / safety and environmental questions
Period: February 2004 – January 2008
Participants: BGR

CO₂SINK: Storage of CO₂ from a biomass power station in aquifers (near Ketzin)
Modelling and mapping / monitoring and verification / safety and environmental questions
Period: April 2004–March 2009
Participants: GFZ, G.E.O.S, Stuttgart University, RWE Power AG

CO₂STORE: CO₂ storage project in aquifers
Monitoring and verification
Period: 02/03–02/06
Participants: BGR

GESTCO: Assessment of European storage potential for CO₂ from combustion of fossil fuels
Period: June 1999–December 2001
Participants: BGR

ICBM: Investigation of a series of technical challenges in sequestration of CO₂ by the ECBM method (Enhanced Coal Bed Methane Recovery)
Period: October 2003–October 2006
Participants: Deutsche Steinkohle AG

Dynamis: Towards Hydrogen and Electricity Production with Carbon Dioxide Capture and Storage
Goal of this project is to investigate possible ways of low-cost industrial hydrogen production with integrated CO₂ capture and storage. Funding from the EU and a consortium of industrial partners
Period: 36 months starting March 2006
Participants: BGR

CO₂-Geonet: European Network of Excellence on Geological Storage of CO₂
Building on the findings of previous EU research projects, the partners in this network together coordinate development of R&D work in order to consolidate Europe's leading position in this field.
Period: April 2004–March 2009
Participants: BGR

ENCAP CO₂: ENhanced CAPture of CO₂
Development of low-CO₂ power station concepts with CO₂ capture before or integrated in combustion (low-CO₂ IGCC, oxyfuel, membranes)
Period: March 2004–March 2009
Participants: RWE, Siemens

OxyCoal-AC: Programme to develop components (phase 1) and bring them together in a pilot plant (phase 2) for the oxyfuel process (combustion in oxygen), with development of high-temperature membrane methods
Funding from BMWA and BMWF
Period: September 2004–2007 (phase 1)
Participants: six departments at RWTH Aachen, RWE Power, E.ON, Siemens, Linde, WS-Wärmeprozessstechnik

RECOPOL: Trial CO₂ storage (near Katowice) in uneconomic deep coal seams
Period: November 2001–November 2004
Participants: RWTH Aachen

ISCC: Innovative in Situ CO₂ Capture technology for solid fuel gasification
The project has the aim of process-integrated capture of storable CO₂ during lignite gasification (CO₂ > 90 %)
Period January 2004–December 2006
Participants: Stuttgart University, IVD

GeoCapacity: Assessing European Capacity for Geological Storage of Carbon Dioxide
The goal of this project is to create a European information system on the distribution of CO₂ sources and storage possibilities. The project integrates and builds on the results of preceding GESTCO and CASTOR projects, and adds in particular data for the new EU member states in eastern Europe. The research project is funded by the European Union and a consortium of industrial partners.
Period: January 2006–January 2009
Participants: BGR

Research programmes of selected european states

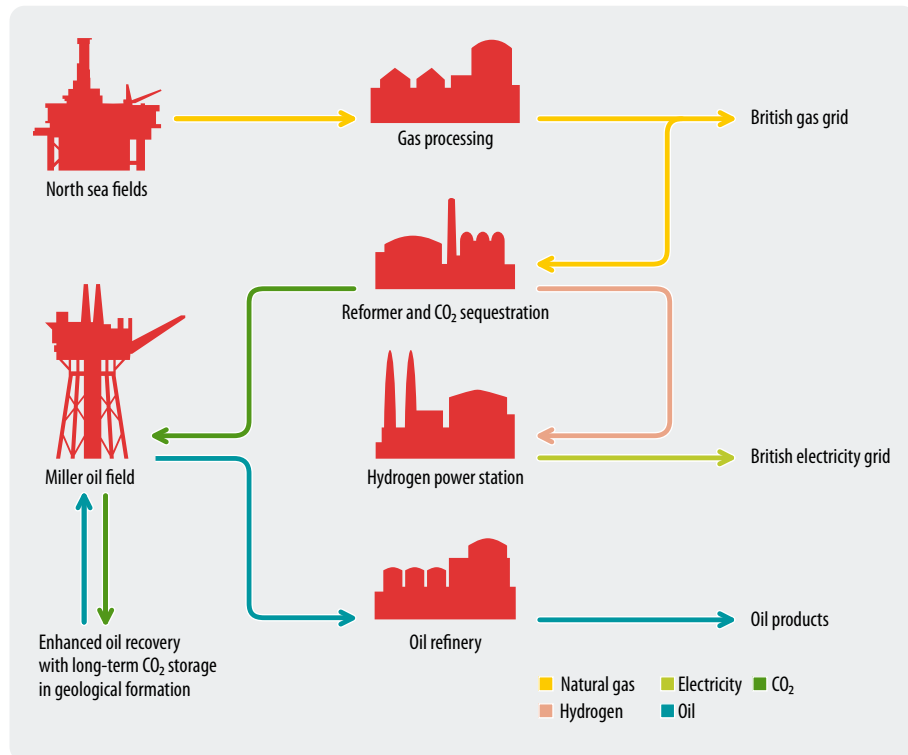
The UK government's **CATS** initiative (Carbon Abatement Technology Strategy) is a research and demonstration programme for furthering the development of 'zero-emission technologies' and increasing efficiency in the field of coal-fired power stations. This is a ten-year programme also focusing on international cooperation in this field.

Also in the UK the **Carbon Capture and Storage Association (CCSA)** has been founded. This is an alliance of companies – largely from the energy supply and plant engineering sectors – that are interested in working to develop geological storage and representing their interests in this field.

Also worth mentioning is the Dutch CCS research programme **CATO** (CO₂ Capture, Transport and Storage in the Netherlands), led by the Utrecht Centre for Energy Research (UCE) and supported by Dutch industry, research institutes, universities and environmental organisations. The goal of this programme is to demonstrate under what conditions CCS can be integrated in a sustainable energy system, taking into consideration economic, technical, social and ecological aspects. The programme has total funding of €25.4 million for the period from 2004 to 2008.

In Norway offshore natural gas extraction is subject to a CO₂ tax. In 1996 this led Statoil to begin storing CO₂ coming out of the **Sleipner** gas field (where the extracted gas mixture contains 9 % CO₂) in a saline aquifer located

Fig. A-6:
Electricity generation using
hydrogen at Peterhead,
Scotland (BP Sustainability
Report 2005)



above the gas field (the Utsira Formation) (1 Mt/a). Furthermore Statoil and the Anglo-Dutch Shell company drew up plans to build a combined cycle power station at Tjeldbergodden in Norway by 2012 at the latest and transport the carbon dioxide emissions to the Draugen and Heidrun oil and gas fields where the captured CO₂ was to be used for EOR/EGR, with the outcome of storing 2–2.5 Mt CO₂ annually. This project has, however, since been abandoned for reasons of cost.

The **CRUST** project, which has been operating since March 2005, represents the first attempt to inject CO₂ into a gas field that is still producing. This pilot project has begun by storing 20,000 tonnes of CO₂ annually; it is planned to increase that figure later to 480,000 tonnes per year. In terms of its approach the project can be designated as enhanced gas recovery (EGR), but its prime concern is in fact to research the migration behaviour of CO₂ rather than actually to increase the gas recovery rate. The gas produced has a high CO₂ share of approx. 13 % (IEA 2005). The project is 90 % funded by the Dutch Economics Ministry, so it has to date required little funding from the private sector (the remaining 10 % are provided by Gaz de France).

CRUST involves capturing CO₂ from the produced gas and then returning it into the reservoir. The Netherlands, incidentally, has a pricing regime for CO₂-free electricity which in principle would also include electricity generated from fossil fuels, presuming the CO₂ involved is withdrawn from the atmosphere.

An integrated project reforming natural gas to hydrogen and CO₂ was planned by BP in conjunction with Cono-

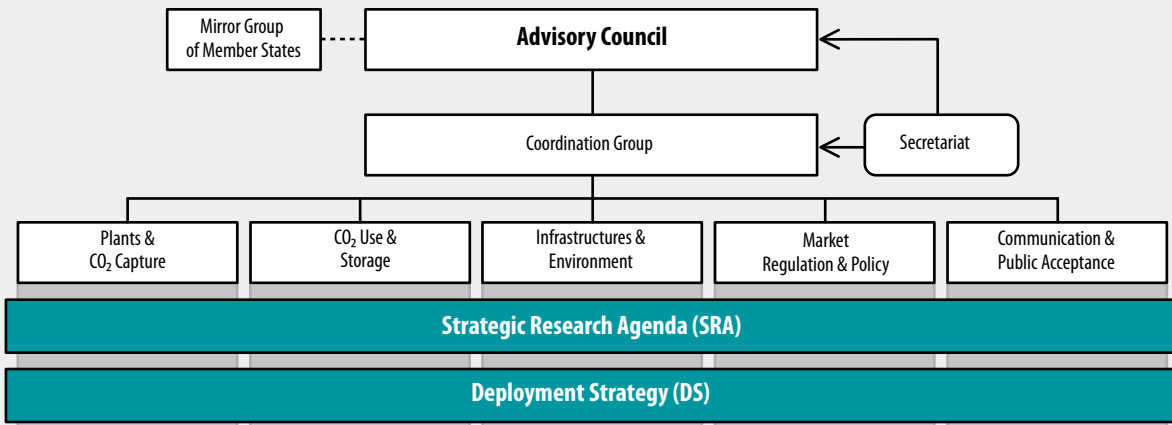
Phillips, Shell and Scottish and Southern Energy at **Peterhead** in Scotland (see Fig. A-6). The hydrogen was to be used to fuel a CC power station capable of generating electricity to supply more than 700,000 households. Per year 1.8 million tonnes of CO₂ were planned to be transported offshore and injected into the Miller oil field at a depth of more than three kilometres below the seabed, which would extend the productive life of the oil field by fifteen to twenty years and increase the yield (BP 2005). Actually this plant is now to be built in the United Arab Emirates in Abu Dhabi. According to BP, the UK government delayed its financial contribution (The Scotsman 2008).

Development perspectives in Europe

As well as the international and US-American information platforms and networks, the European Union offers information platforms and networks as part of its research programmes.

The establishment of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ETP **ZEFFPP** 2005) created a body to coordinate the measures required for reducing CO₂ emissions from electricity generation. Fig. A-7 shows the organisational structure. The Strategic Research Agenda and Strategic Deployment Document produced by working parties define strategies for market introduction and for Europe to achieve the CO₂ reduction goals, divided into immediate measures, measures to be taken by 2030 and beyond then.

Technology Platform ZEFFPP
Organisational Structure



Technology Platform ZEFFPP
Members of Advisory Council

Generators		
Kurt Haege	Vattenfall AB (Chair)	:Germany
Bernhard Fischer	E.ON Energie AG	:Germany
Santiago Sabugal Garcia	ENDESA Generation	:Spain
Johannes Lambertz	RWE Power AG	:Germany
Gennaro di Michele	ENEL	:Italy
Hakon Mosbech	ENRGI E2 A/S	:Denmark

Equipment Suppliers		
Charles Soothill	ALSTOM (Vice-Chair)	:UK
Harry Lampenius	Foster Wheeler	:Finland
Iain Miller	Mitsui Babcock	:UK
Norbert Koenig	Siemens AG Power Generation	:Germany
Francois Jackow	Air Liquide	:France
Giuseppe Zampini	Ansaldo Energia SpA	:Italy

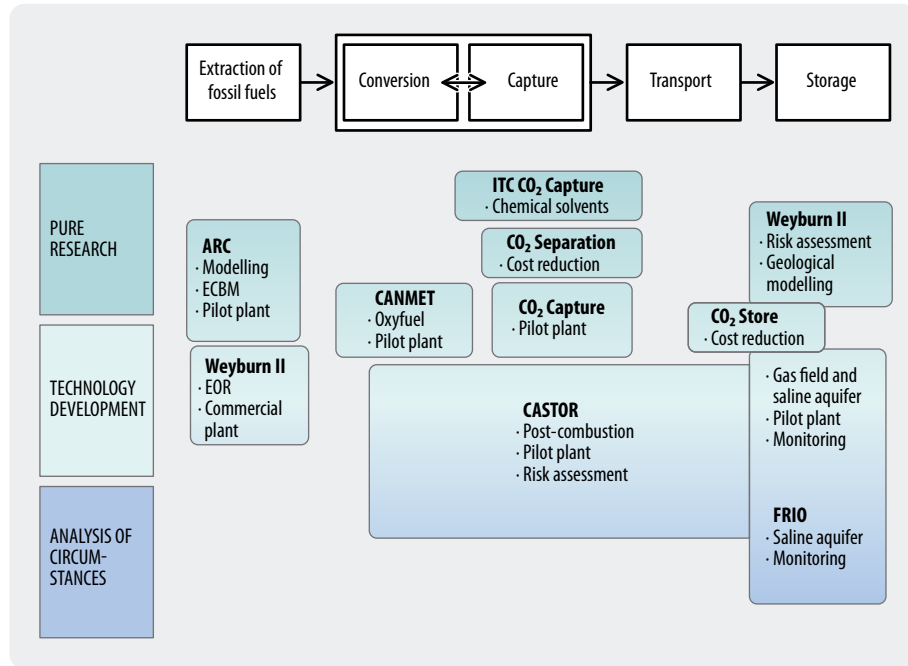
Oil/Gas		
Gardiner Hill	BP (Vice-Chair)	:UK
Jean-Michel Gires	Total SA	:France
Philippe Lacour-Gayet	Schlumberger	:France
Graeme Sweeney	Shell Gas and power	:UK
Arve Thorvik	Statoll	:Norway

Research		
Olivier Appert	IFP (Vice-Chair)	:France
Antonio Valero	CIRCE (Vice Chair)	:Spain
Niels Peter Christensen	GEUS	:Denmark
Josek Dubinski	CMI	:Poland
David Falvery	BGS	:UK

NGOs		
Frederic Hauge	The Belona Foundation	:Norway
Kirsten Macey	Climate Action Network Europe	:Belgium
Stephan Singer	WWF International	:Belgium

Fig. A–7: Organisational structure and members of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEFFPP) (http://ec.europa.eu/research/energy/pdf/zeffpp_power_plant_en.pdf)

Fig. A–8:
CSLF project categories
and research areas
(Hake 2005)



A.3.2 International Activities and Political Strategies

The Carbon Sequestration Leadership Forum (CSLF) is an internationally important climate protection alliance that was set up in 2003 on the initiative of the United States. The CSLF works for the development of cost-effective capture and storage technologies, low-cost CO₂ transport and long-term stability of storage, and promotes the exchange of information about CCS activities in the field of climate protection. As well as the EU, twenty other states are also members of this initiative (www.cslforum.org). Currently about seventeen projects supported by the CSLF are under way across the world. Fig. A–8 shows the research priorities.

One of these projects is the Enhanced Coalbed Methane Recovery Project of the Alberta Research Council (ARC) in Canada, which is running a trial to investigate whether CO₂ can be injected into a deep coal seam and how the methane released in the process can be used (ECBM). The results will be used as the basis for the development of China's Coalbed Methane Technology/Carbon Dioxide Sequestration Project.

The International Energy Agency (IEA) is conducting the following work in the field of CCS: the Working Party on Fossil Fuels promotes the development of 'zero emissions technologies' and coordinates international cooperation and exchange in this field. The Clean Coal Centre stimulates the innovation and use of coal as a 'clean fuel' by identifying the potential of apparently suitable technologies, identifying open questions and jointly publishing the results of cooperative projects. The Greenhouse Gas R&D Programme analyses and assesses various technical options for their potential for climate protection, and publishes the results.

Certain countries have set up their own CCS programmes; these are briefly outlined below. The Australian COAL 21 programme aims to reduce greenhouse gas emissions from electricity generation using coal through a joint initiative supported by the government, industry and research bodies.

The EU-China Partnership on Climate Change established in autumn 2005 includes an EU-China Action Plan on Clean Coal which seeks to promote joint development and implementation of 'near zero emission coal projects'. The first concrete agreement in this context was concluded in January 2006 between the UK and China: a three-year feasibility study will begin by examining the practicality of various concepts and investigating the options for geological storage of CO₂. This shows that research efforts and also first practical steps in the field of CCS are beginning to extend beyond the EU and the United States.

The United States has published an internationally significant policy strategy in the form of the *Carbon Sequestration Technology Roadmap and Program Plan* (DoE 2003/2005), which covers the following three fields of research:

A. Core R&D The goal of this programme is to advance sequestration research and develop new sequestration technologies through to the market launch phase. The core programme has five areas:

- CO₂ capture,
- CO₂ storage,
- Monitoring, mitigation and verification,
- Control of other greenhouse gases,
- New concepts.

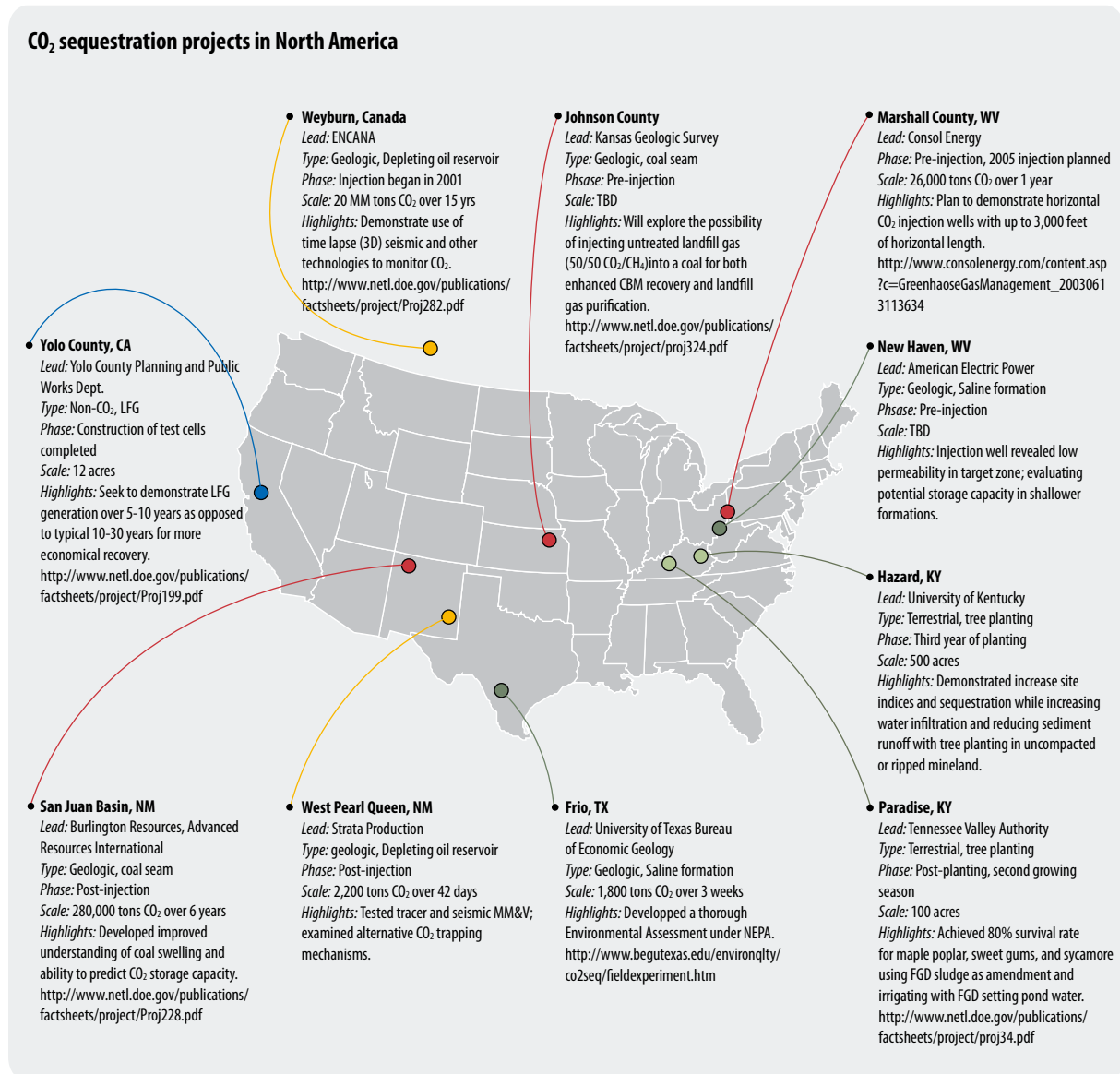


Fig. A-9: CCS demonstration projects in the United States (DoE 2005, Department of Energy)

These research areas are complemented by demonstration projects focusing on different aspects, see Fig. A-9.

B. Infrastructure development The US Department of Energy (DoE) in 2003 initiated seven regional CO₂ sequestration partnerships with the goal of developing an infrastructure for future CCS pilot projects. This partnership has given rise to a national network of firms and experts aiming to advance the use of CCS, and to a Carbon Sequestration Atlas of the United States that identifies priority regions for CCS pilot projects.

C. Program management This is the R&D management programme. In a bid to deploy its budget and pursue its research goals as effectively as possible, the DoE has set up public-private partnerships, and

engaged in national and international cooperation, analyses and project evaluation, and proactive public relations work.

As part of the broad-based Clean Energy Programme, which has funding of almost \$2,000 million of which 80 % is provided by the state, the DoE has launched the **FutureGen** venture with the aim of producing the prototype for a new commercial coal-fired power station technology. It involves the biggest electricity generating and coal mining corporations in the United States, including RAG AmericanCoal and Eon. The technology is to be based on coal gasification, aiming for efficiency of 60 % and a CO₂ capture rate of 90 %. As well as electricity, hydrogen is also to be generated for other applications, for example for fuel cells for road transport. The aim is to generate electricity at a cost no more than 10 % higher than with current technologies.

RAG Coal International is also involved in another research project in the United States, the Zero Emission Coal to Hydrogen Alliance (**ZECA**), which also tackles the issue of generating electricity from coal without CO₂ emissions. The goal of this project is to safeguard coal's long-term future as a fuel. The starting point for the research is a process where the CO₂ emissions produced when coal is burned to generate electricity are not released but fixed in mineral form. Initial experience is to be gathered from an industrial-scale power station based on fuel cell technology, which is to begin operating in the second half of this decade. Further details on the ZECA project can be found at www.zeca.org.

One commercially run storage project in the United States and Canada is found at the **Weyburn** oil field (Canada), where CO₂ is used for enhanced oil recovery (EOR).² The CO₂ is supplied by a pipeline system from a gasification plant in North Dakota (USA). After injection it remains underground.

One place where CO₂ is also already being used industrially is the **Shady Point** CHP plant in the state of Oklahoma, where 200 tonnes of CO₂ daily are captured from a part of the flue gas and supplied to the food industry.

At **Carson**, California, there are plans to build a hydrogen power plant using oil coke. This would demonstrate that low-CO₂ energy can be generated from coal, of which the United States has abundant reserves. After starting operation the Carson project would generate 500 MW of low-CO₂ electricity, enough to supply about 325,000 households in southern California. The plant is also to be used to sequester and permanently store about 4 million tonnes of CO₂ annually. BP and the Edison Mission Group intend to make the final investment decisions in 2008 after preparation of detailed technical and commercial studies. If they go ahead the new power station could come on stream in 2011 (BP 2005).

The **Greater Gorgon Gas Development** in Australia is a project for gas extraction and subsequent LNG production operated by ChevronTexaco. For LNG production (planned annual volume 10 million tonnes) the CO₂ present in the extracted gas must be removed.³ The rest of the extracted gas is transported on in gaseous form to the compressor. The CO₂ to be injected arises largely from LNG production and in other energy-intensive processes, while a smaller part is contributed by the CO₂ in the extracted gas. The storage formation is a saline aquifer underneath Barrow Island, where the LNG plant will also be located. The storage project will cost at least AUS\$300 million (approx. €180 million). According to ChevronTexaco there is no obligation under Australian law to avoid CO₂ emissions. The stated motivation is concern about climate change and the company's responsible attitude to greenhouse gas management (Gorgon 2005).

2 Process whereby water or CO₂ is injected into boreholes to increase the oil recovery rate.

3 The CO₂ would otherwise freeze and damage the equipment.

In Japan and Australia, too – as in most of the road maps – immediate measures to increase efficiency in new power stations are at the top of the agenda. Since 1995 there has been a continuous increase in the steam parameters of new power stations (pressure and temperature) (Santos and Davison 2006). Whereas short- to medium-term attention in Europe and the United States is focused on pre- and post-combustion measures, Japan has made an early choice to prioritise the introduction of fuel cell technologies in combination with coal gasification. Japan and Australia also cooperate in the fields of oxyfuel combustion and integrated drying gasification combined cycle (IDGCC), which is mainly being pursued in Australia. In the joint Hypercoal Project coal is to be demineralised in Australia and used in Japan for low-emissions energy generation.

Also worthy of note are projects initiated by BP/Sonatrach and ChevronTexaco that have already reached the planning stage. In a joint venture between BP and Sonatrach in Algeria, the In Salah CO₂ Geological Storage Demonstration Project, the accompanying CO₂ is separated out as the gas is produced in order to stay within the export specifications (CO₂ content < 0.3 %). The removed CO₂ is not released into the atmosphere as usual but instead injected into a geological formation. All in all, 900,000 to 1,000,000 tonnes of CO₂ annually are to be stored underground in this way. BP says it is motivated by the company's promise to reduce its climate-relevant emissions. BP has an internal emissions trading system where the stored CO₂ can then be converted into certificates. It should be emphasised that most of the CO₂ emissions originate from energy-consuming processes, and the CO₂ from the extracted gas represents only a small proportion (IEA 2005).

Research into CO₂ sequestration also includes the following networks:

Monitoring Network – Founded on 8 November 2004 at a meeting at the University of California Santa Cruz organised by the IEA GHG and BP with the support of EPRI and the American Department of Energy (DoE/NETL).

International Network for CO₂-Capture – The IEA GHG set up the CO₂ Capture Network to serve as a forum and to support research projects in the field of capture. All the members are industrial companies.

International Network on Biofixation of CO₂ and Greenhouse Gas Abatement with Microalgae – The purpose of the Microalgae Biofixation Network is to offer a platform for organisations interested or involved in R&D work aiming to reduce greenhouse gases using microalgae. Members come from the spheres of science and industry and from the American Department of Energy.

ZECA Zero Emission Coal Alliance – A consortium from the United States and Canada composed of eighteen members from government, research organisations and the coal industry. Its purpose is to advance the

German projects in the geotechnologies R&D programme of the Federal Ministry of Education and Research Focusing on 'Exploration, Use and Protection of Underground Resources'

CO₂-TRAP: Development and evaluation of innovative strategies for permanent storage of CO₂ in geological formations

RWTH Aachen, Bayreuth University, Stuttgart University, RWE-DEA AG (Hamburg), RWE Power AG (Cologne), Saar Energie GmbH (Saarbrücken), Deutsche Steinkohle AG (Herne), Deutsche Montan Technologie (Essen)

Enhanced Gas Recovery (EGR): Storage of CO₂ in deep natural gas deposits with the possibility of enhanced gas recovery – a feasibility study
Clausthal Technical University, BGR (Hannover), Vattenfall Europe, EEG (Gommern), E.ON-RuhrGas, Wintershall (Kassel)

COSMOS: CO₂ storage and development of monitoring and safety technologies

GeoForschungsZentrum Potsdam, Deutsches Brennstoff Institut – Gastechnologisches Institut GmbH (dbi-gti), Vattenfall Europe Mining AG (Cottbus), Karlsruhe University, RWE Power AG (Essen)

RECOBIO: Recycling of CO₂ through microbial biochemical conversion into methane (CH₄) deep underground
GEOS-Freiberg Ingenieurgesellschaft mbH, Dresdner Grundwasser-forschungszentrum e.V. (DGFZ)

CDEAL: Fixing CO₂ through mineral reactions in acid pit water and flooded disused pits in an open-cast lignite mining area
Freiberg University of Mining and Technology

CO₂CRS: High-resolution underground imaging for CO₂ storage using the CRS method

Trappe Erdöl Erdgas Consultant (Isernhagen), Karlsruhe University, Free University of Berlin

Development of the SPIN instruments system for exploration and monitoring for underground CO₂ storage using nuclear magnetic resonance
Geohydraulik Data, TU Berlin, FH Gelsenkirchen

CHEMKIN: Real-time monitoring of the chemical and kinetic behaviour of carbon dioxide during geological sequestration

GeoForschungsZentrum (Potsdam), Umwelt- und Ingenieurtechnik GmbH (Dresden), Potsdam University, Clausthal Technical University, Optimare GmbH (Wilhelmshaven).

Numerical investigations of CO₂ sequestration in geological formations – problem-based benchmarks

Stuttgart University, Deutsche Montan Technologie (Essen)

CO₂-UGS-Risks: Integrated safety and risk analysis of CO₂ storage in Germany

Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH (Braunschweig)

development of new and highly efficient technologies for electricity generation and/or hydrogen production from coal 'with zero atmospheric emissions'.

EnergyNet – A national Canadian network covering the spheres of science and industry and government ministries for developing future perspectives and new technologies to open up a broad supply of affordable and environmentally sound energy.

A.3.3 CCS Projects in Germany

In Germany too, projects in the field of CO₂ capture and storage are already being conducted or are under development. In addition German institutions are also involved in various EU-wide research projects (see chapter 17.3.1).

One particularly important project is the EU-funded **CO₂Sink** led by the Potsdam-based Geoforschungsinstitut, where CO₂ is injected into a geological formation under real conditions. Seventeen different partners are now involved in this project, including power companies. Storage is in a porous geological formation underneath an underground storage facility for natural gas at Ketzin near Berlin. One of the aims is to use different monitoring methods to track the behaviour of the stored gas and thus gain knowledge about long-term stability.

In its research and development programme **GEO-TECHNOLOGIEN** the Federal Ministry of Education and Research has since March 2005 been funding ten interdisciplinary research groups from scientific institutes and private industry with almost €7.5 million. The goal of this research programme, which is initially to run for three years, is to examine the technological, ecological and economic perspectives of underground storage of the greenhouse gas CO₂ (see the overview in the text box).

The Federal Ministry of Economics initiated the **COORETEC** research concept, which is designed to lead to the realisation of low-emissions fossil-fuelled power stations through an alliance of partners from the spheres of science and industry. The programme aims to show how the technologies required for highly efficient, largely emissions-free and economic coal- and gas-fired power stations could be developed by 2020. One offshoot of this programme is the **COORIVA** research project (CO₂ reduction through integrated gasification and capture), whose aim is to develop an IGCC concept making use of experience already gathered in industrial-scale projects and integrating CO₂ capture. In parallel investigations are already under way into the potential of gasification of lignite and coal, the creation of modelling tools and upscalear studies.

Among the power companies, RWE has announced the construction of an IGCC plant with CO₂ capture by

2014, and in May 2006 Vattenfall began building a demonstration oxyfuel power station at Schwarze Pumpe, which is due to begin operations in 2008.

A.4 Central Issues for Planning a CO₂ Transport Infrastructure (to Chapter 8)

Central questions that could guide the process of designing and setting up a CO₂ transport infrastructure are listed below:

1. What are the similarities and differences in the handling of natural gas and CO₂?
 - physical and thermodynamic properties,
 - risk management,
 - corrosion,
 - pipeline transport (pressure, cross-section, volume and mass flows, compressor capacity).
2. Where is experience with handling and transporting CO₂ or with transporting gases with similar properties (e.g. LPG) located already?
3. Who is likely to be operating CO₂ pipelines?
4. What combinations of onshore/offshore transport systems are conceivable (e.g. onshore pipelines + main pipeline + intermediate storage + ship loading + ...) and which of these make sense?
5. What infrastructure questions arise (loading/unloading systems, competition with existing shipping, etc.)?
6. What selection of route makes sense (in economic and ecological terms and in relation to questions of risk and acceptance)?
7. How many compressor stations (electrical/gas-powered) must be constructed, and where?
8. What questions are relevant for cost analysis?
 - € per kilometre of pipeline (as function of diameter, pressure, volume/mass flows, topography...).
 - € per tonne-kilometre of transported CO₂ (as function of phase, capacity, maturity of technology ...).
 - Cost of additional equipment (liquefiers, compressors, collectors, measuring stations...).
9. What might the learning curves for CO₂ pipelines look like (individual pipelines, networks, etc.)?
10. What questions are relevant when analysing the timeframe?
 - When could which power stations and CO₂ sinks come into operation?
 - When will which sinks be full?
- How long would it take to set up a CO₂ pipeline infrastructure (time for planning, approval and construction)?
- When will which CO₂ intermediate storage facilities be required, and when will they be available (for offshore ship transport and onshore road and rail transport)?
11. What approval procedures and planning periods are generally required for building new pipelines or expanding existing ones?
12. What problems can arise if CO₂ pipelines are constructed parallel to existing natural gas pipelines (e.g. space requirement where route is narrow, acceptance if additional forest clearance necessary)?
13. What CO₂-specific requirements are the pipeline network and components such as compressors, measuring stations subject to in terms of safety, corrosion, etc.?
14. Where CO₂ is transported in the supercritical state: is it sufficient to compress once at the beginning (at the power station) or are additional compressor stations required? If so, after what distances or pressure losses?
15. Might disused town gas pipelines be suitable for CO₂ transport (following conversion)? If so, what is their geographical distribution (transport from where to where) and what transport capacities do they provide?

A.5 Data Used for Analysing Mass Flows of Fuel and CO₂ (to Chapter 10)

See Tables A-3 and A-4.

Table A-3: Analysis of additional fuel quantities required for CCS and quantities of CO₂ to be disposed of for different power station types (**electricity production**)

1) CO ₂ quantities														
Fuel	Process	Specific CO ₂ emissions (fuel)		Power station output (net) [MW _{el}]	Efficiency η_{el}		Specific CO ₂ emissions (electricity)		Full load hours [h/a]	Annual electricity production [MWh _{el} /a]	Annual production of CO ₂		Capture rate [%]	CO ₂ to be disposed of [t _{CO2} /a]
		[g _{CO2} /MJ _{fuel}]	[g _{CO2} /kWh _{fuel}]		without CCS [%]	with CCS [%]	without CCS [g _{CO2} /kWh _{el}]	with CCS [g _{CO2} /kWh _{el}]			without CCS [t _{CO2} /a]	with CCS [t _{CO2} /a]		
Lignite	Steam turbine	112	403	700	46%	34%	877	1,186	7,000	4,900,000	4,294,957	5,810,824	88%	5,113,525
	Steam turbine	92	331	700	49%	40%	676	828	7,000	4,900,000	3,312,000	4,057,200	88%	3,570,336
	Steam turbine, Oxyfuel	92	331	700	49%	38%	676	872	7,000	4,900,000	3,312,000	4,270,737	99,5%	4,249,383
Natural gas	IGCC	92	331	700	50%	42%	662	789	7,000	4,900,000	3,245,760	3,864,000	88%	3,400,320
	CC	56	202	700	60%	51%	336	395	7,000	4,900,000	1,646,400	1,936,941	88%	1,704,508
Extra light fuel oil	CHP	74	266	2	38%	–	701	–	4,000	8,000	5,608	–	–	–

2) Fuel quantities												
Fuel	Process	Fuel consumption		Difference with / without CCS [MWh/a]	Calorific value of fuel [MJ/kg]	Fuel density	Fuel consumption		Additional fuel for CCS			
		without CCS [MWh/a]	with CCS [MWh/a]				without CCS	with CCS				
Lignite	Steam turbine	10,652,174	14,411,765	3,759,591	8.6	1 kg/kg	4,459,050 t/a	6,032,832 t/a	1,573,782 t/a			
	Steam turbine	10,000,000	12,250,000	2,250,000	29.4	1 kg/kg	1,224,490 t/a	1,500,000 t/a	275,510 t/a			
	Steam turbine, Oxyfuel	10,000,000	12,894,737	2,894,737	30.4	1 kg/kg	1,184,211 t/a	1,527,008 t/a	342,798 t/a			
Natural gas	IGCC	9,800,000	11,666,667	1,866,667	29.4	1 kg/kg	1,200,000 t/a	1,428,571 t/a	228,571 t/a			
	CC	8,166,667	9,607,843	1,441,176	46.5	0.780 kg/m ³	810,587,262 m ³ /a	953,632,073 m ³ /a	143,044,811 m ³ /a			
Extra light fuel oil	CHP	21,053	–	–	42.7	0.845 kg/l	2,100,508 l/a	–	–			

Shaded cells are modifiable starting parameters
Source for specific fuel data (emissions, calorific value, density): Bay (fU) (2004)

Table A-4: Analysis of additional fuel quantities required and quantities of CO₂ to be disposed of for different synthesis gas plants (H₂ production)

1) CO ₂ quantities															
Fuel	Process	Specific CO ₂ emissions (fuel)		Net output		Process efficiency η		Specific CO ₂ emissions (H ₂)		Full load hours [h/a]	Annual H ₂ production [MWh _{H₂} /a]	Annual production of CO ₂		Capture rate [%]	CO ₂ to be disposed of [t _{CO₂} /a]
		[g _{CO₂} /MJ _{HHV}]	[g _{CO₂} /kWh _{HHV}]	without CCS [MWh _{H₂}]	with CCS [MWh _{H₂}]	without CCS [%]	with CCS [%]	without CCS [g _{CO₂} /kWh _{H₂}]	with CCS [g _{CO₂} /kWh _{H₂}]			without CCS [t _{CO₂} /a]	with CCS [t _{CO₂} /a]		
Coal	Gasification	92	331	560	522	59%	55%	561	602	8,000	4,480,000	2,514,875	2,697,775	88%	2,374,042
Natural gas	Steam reforming	56	202	350	329	74%	69%	274	292	8,000	2,800,000	766,957	816,903	71%	580,001

2) Fuel quantities												
Fuel	Process	Fuel consumption		Difference		Calorific value of fuel		Fuel density		Fuel consumption		Additional fuel for CCS
		without CCS [MWh/a]	with CCS [MWh/a]	without / with CCS [MWh/a]	without / with CCS [%]	[MJ/kg]	[kWh/kg]	without CCS	with CCS	without CCS	with CCS	
Coal	Gasification	7,593,220	8,145,455	552,234	7%	29,4	8,17	1 kg/kg	929,782 t/a	997,403 t/a	67,621 t/a	
Natural gas	Steam reforming	3,804,348	4,052,098	247,751	7%	46,5	12,92	0,780 kg/m ³	377,602,762 m ³ /a	402,193,390 m ³ /a	24,590,628 m ³ /a	

Shaded cells are modifiable starting parameters

Efficiency figures relate to the heating value of H₂ (3.00 kWh/Nm₃)

Conversion factor for H₂ calorific value (3.55 kWh/Nm³ / 3.00 kWh/Nm³) = 1.18

Source for specific fuel data (emissions, calorific value, density): BayLU (2004)

References

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