Wuppertal Institute
for Climate, Environment
and Energy

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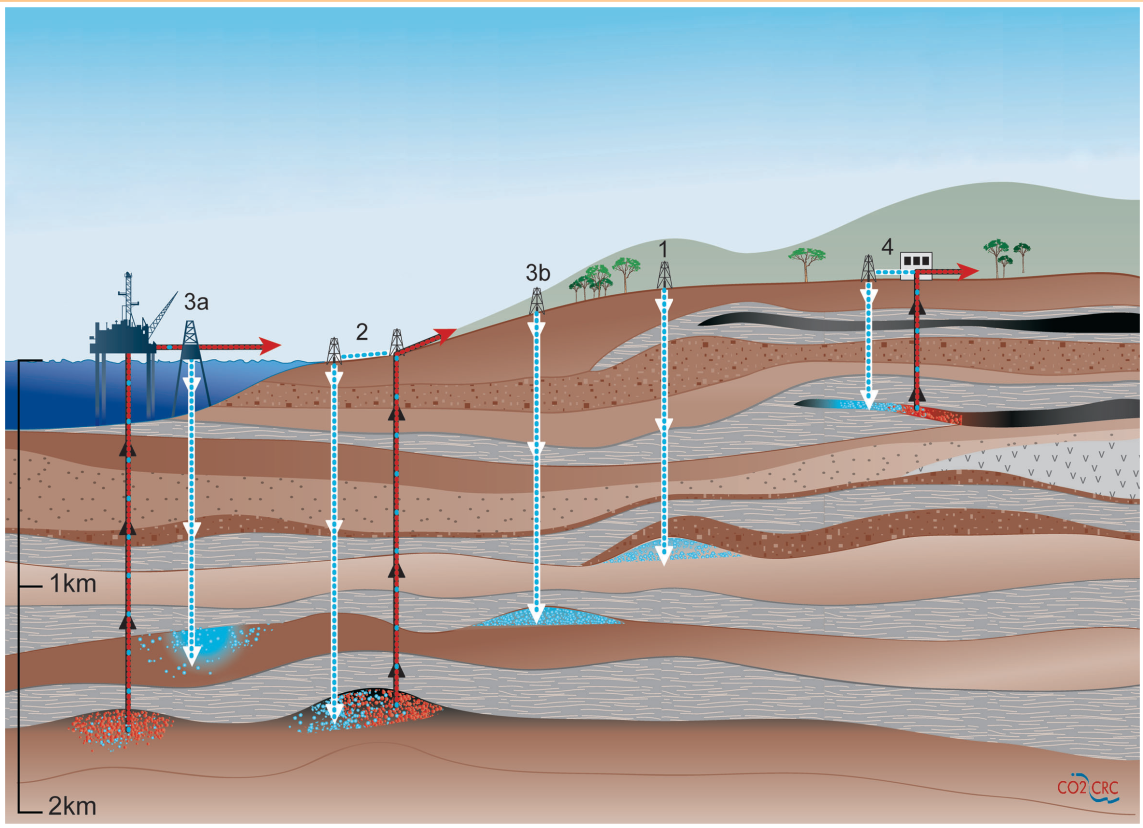
CO_2-Capture and Geological Storage as a Climate Policy Option

Technologies, Concepts, Perspectives

WUPPERTAL SPEZIAL 35e



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Contents

1 Introduction

The idea of removing carbon dioxide from flue gas and industrial gas flows and putting it into suitable long-term storage sites is referred to as Carbon Capture and Storage (CCS). In this publication we take a closer look at this new line of technologies, describing its current status and outlining the prospects for development. Our approach is both diagnostic and analytical, identifying the questions a technology assessment poses and showing the steps that need to be taken to implement CCS.

CCS is currently moving to the centre of climate policy discussion. Nonetheless this line of technologies is still the subject of controversial discussion. On the one hand there is a clear hope that these technologies will open up opportunities to use fossil fuels without harming the climate and thus make it possible to continue using oil, natural gas and above all coal even under a stricter climate regime. Accordingly, numerous R&D projects have been initiated all over the world, and various demonstration projects are at the planning or implementation stage. On the other hand, CCS (especially the storage part) has given rise to considerable scepticism from an ecological point of view.

Chapter 2 starts by explaining the climate policy background that forms the major motivation for developing and introducing CCS. The technologies are described in Chapter 3, along with examples of applications and information on the experience to date. Chapter 4 discusses the technical, economic and ecological requirements (the necessary factors for success) for implementing CCS, while Chapter 5 focuses on the complementary institutional and regulatory framework that would be necessary to provide legal certainty for potential investors and to create economic incentives through integrating CCS in national and international climate protection policies. Chapter 6 provides an outlook and a summary of the required policy actions.

2 The Problem of Global Warming

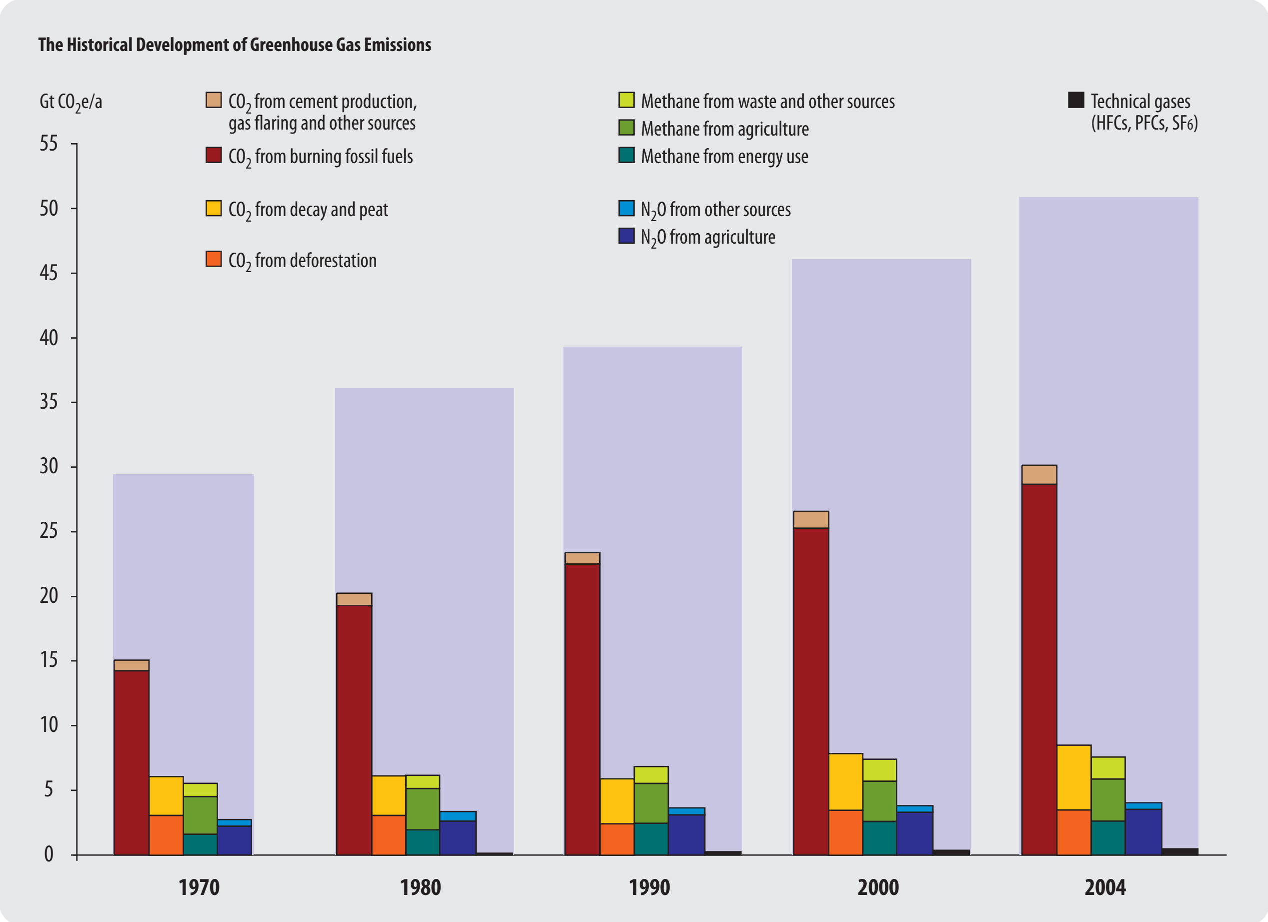
Global warming caused by human activity represents one of the greatest challenges of the twenty-first century. In the light of our growing knowledge about the causes and effects, the current state of the climate and the limits of tolerable climate change, there is no alternative to urgent corrective action. Today CCS is seen as one option alongside other technologies that could make a significant contribution to reducing greenhouse gas emissions. This chapter explains why action is needed on climate change and describes the potential of CCS as an element of climate protection from the perspective of various institutions.

a. An Overview of the Current Climate Discussion

Scientific observations show that the earth's mean temperature has risen by 0.8°C over about the last 100 years. According to the latest findings of the Intergovernmental Panel on Climate Change (IPCC), natural causes are responsible for no more than 10 percent of the rise while at least 90 percent is due to anthropogenic effects resulting overwhelmingly from an increase in the concentration of greenhouse gases in the atmosphere. The release of carbon dioxide (CO_2) through the burning of fossil fuels plays a special role here.

The IPCC estimates that a doubling of the concentration of CO_2 will probably cause the average global temperature to rise by between 2.0 and 4.5°C, with the "best estimate" being about 3.0°C (or about 0.5°C higher than in earlier estimates). In other words, the potential effects of climate change have accelerated.

In accordance with Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) and in line with the recommendations of climate scientists, the European Council considers an increase of 2°C over the pre-industrial temperature as the maximum tolerable limit (European Council 2005). The decision of the EU summit of March 2007 to reduce the EU's greenhouse gas emissions to 20 percent below their 1990 level by 2020 is a response to the implications of that limit (European Council 2007). If other industrialised countries commit themselves to comparable emission reductions, and the advanced developing countries also agree to face up to their responsibilities, the EU intends to reduce its own greenhouse gas emissions by 30 percent. The first step towards reaching this goal has been taken, with agreement on a binding expansion target for renewable energies (20 percent share of primary energy supply by 2020 plus 10 percent share for biofuels). The Action Plan for 2007–09 also names a clear increase in energy efficiency and the development of CO_2 capture and storage technologies as important tasks.



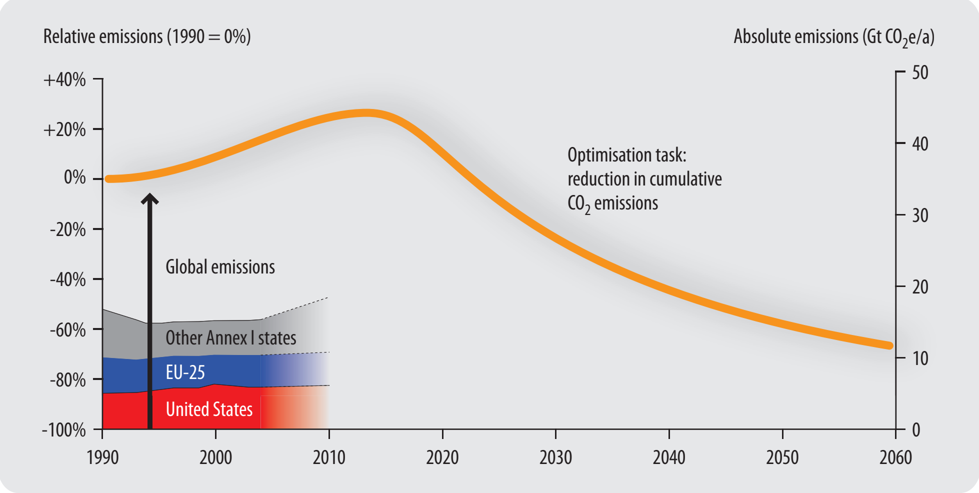
b. Greenhouse Gas Emissions and Emission Sources

Figure 1:
The Historical Development of Greenhouse Gas Emissions (after IPCC 2007)

Among all the causes of anthropogenic climate change, energy-related CO_2 emissions play a special role. Figure 1 shows an overview of the historical development and the current emissions levels of all relevant greenhouse gases. To allow for the different effects of different gases, the figures are given in tonnes of CO_2 equivalent (CO_2e), because the greenhouse gas effect of certain other molecules is considerably higher than that of CO_2. Of the 38.7 Gt CO_2e/a of greenhouse gases emitted in 1990, about 21 Gt/a were energy-related CO_2 released through the burning of fossil fuels. Another 8 Gt/a were accounted for by deforestation and 9 Gt/a were non-CO_2 gases, primarily methane (from anaerobic carbon metabolism, especially from ruminants and from rice cultivation).

By 2004 greenhouse gas emissions had risen to 51 Gt CO_2e/a, with a large part of the growth resulting from the increase in energy-related CO_2 emissions. If this development continues it will be impossible to stay within the aforementioned acceptable limit for temperature increase. A clear turnabout of the trend is required: the increase in greenhouse gas emissions must first be slowed down and then reversed. Seen from today's perspective, the 2°C target is only achievable if global emissions can be reduced below 10 Gt CO_2e/a in the longer term (Figure 2). Under these conditions, reducing emissions below the level of 15 Gt CO_2e/a by 2050 would appear to be an appropriate first step. That would mean more than halving the 1990 level. For the industrialised countries, which the European Council believes should be taking a leading role in climate protection, this would mean reducing greenhouse gas emissions by 60 to 80 percent by the middle of this century.

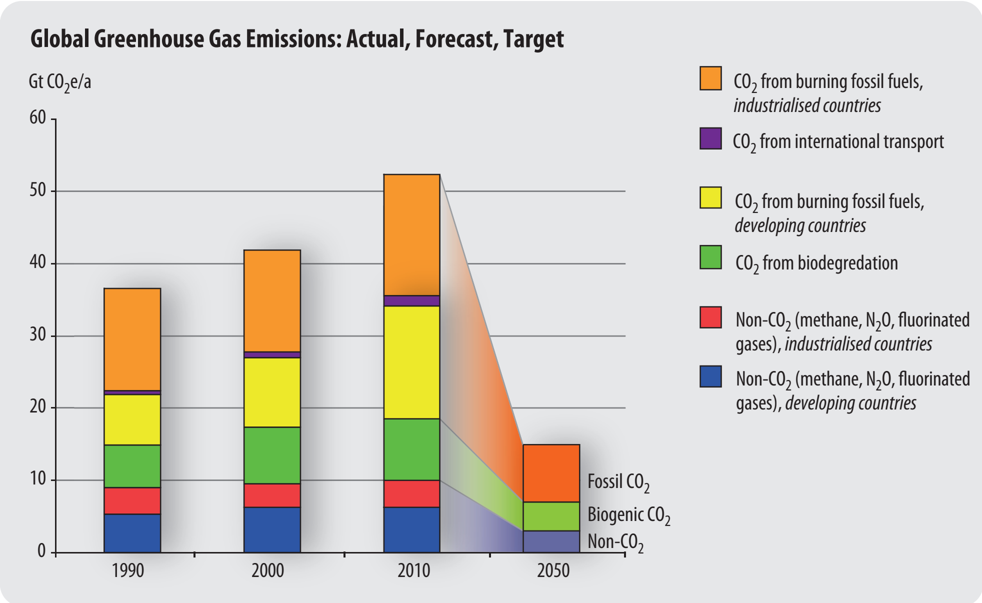
Figure 2:
Necessary Reduction in Greenhouse Gas Emissions (after Meinshausen 2006; Greenhouse Gas Emissions including emissions from deforestation and other land use)



However, because the climatic response to greenhouse gas emissions — temperature rise — is time-lagged, success or failure will depend less on the level of emissions in the target year than on the shape of the emission curve. It is the sum of all emissions that determines the decisive variable for climate change: greenhouse gas concentration. Put another way, we should aim to keep the area under the curve in Figure 2 — as a measure of cumulative emissions — as small as possible. When it comes to limiting climate change it is important not only to break the trend (of rising emissions) but also to ensure that the level of total emissions accumulated to date is reduced as quickly as possible.

A simple calculation makes the difference clear: The rise in emissions in the past two decades, 1990–2010, resulted in additional cumulative emissions of 80 Gt. But over those 20 years the original 1990 emissions level also produced a steady flow of 39 Gt/a, or cumulated over the whole period a total of almost 800 Gt. The conclusion that must be drawn is that stopping a further rise in emissions is only part of the task (Figure 3); the real challenge is to achieve a significant reduction in the level reached to date. This means tackling both tasks together, for which technological options will need to be developed and introduced.

Figure 3:
Global Greenhouse Gas Emissions over Time, Forecast for 2010 and Target for 2050 (source: Wuppertal Institute)



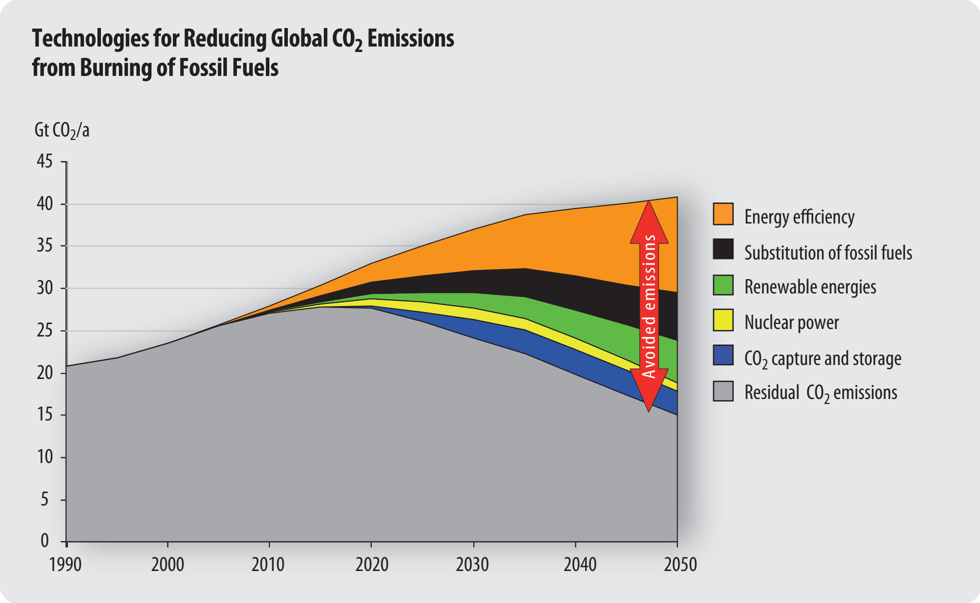


Figure 4:
EU Proposal for the Contribution of Different Climate Protection Options to Reducing Combustion-related CO_2 Emissions (after CEC, 2007)

c. Climate Change Policy Options

Figure 4 shows the options for action to be taken in the direction outlined above for the example of energy-related CO_2 emissions. It represents a European scenario for a possible reduction in global energy-related CO_2 emissions (CEC 2007). According to it a combination of different measures would reduce emissions by 12 Gt CO_2/a in comparison to the business-as-usual curve by 2030, and about then to begin reducing emissions below the 1990 level. It is unclear whether such a course would be sufficient to meet the 2°C target, but it would certainly represent a significant step in that direction.

Alongside efficiency increases, changes in the type of fuel used (especially replacing coal with gas), expanding renewable sources of energy and deploying nuclear power (albeit in a rather limited way), a major means of emissions reduction is expected to be CCS. Figure 4 shows the respective ranking the EU assigns to the different solutions based on when they are expected to come on line. The most important measure is improving energy efficiency, which relatively quickly makes a substantial contribution, followed by replacement of coal by natural gas, which could have an impact at a relatively early stage. Expansion of renewable energy sources comes third, slightly later and with rather less volume. At the end come the major technical solutions: nuclear power with a relatively low overall contribution, and CO_2 capture. The latter's share — if the levels of targeted contributions remain unchanged — will already have reached its maximum by 2035, after which it will be overtaken in volume by renewables.

Alongside the EU's projections, there are also several other analyses that examine the feasibility of significant emission reductions at the global level. The World Energy Outlook 2006, published by the International Energy Agency (IEA), includes an "Alternative Policy Scenario" (APS) that sketches out a development trajectory based on the implementation of climate protection measures already under discussion in the individual countries. Here the energy-related CO_2 emissions are reduced by 6.3 Gt/a by 2030 compared to business-as-usual, but there would still be an absolute increase in annual emissions from 26 Gt/a in 2004 to 34 Gt/a in 2030.

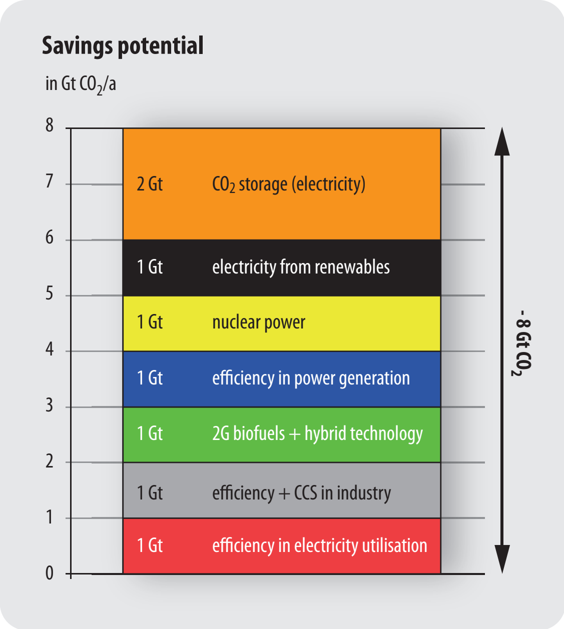


Figure 5:
Possible Additional CO_2 Reductions Beyond the "Alternative Policy Scenario" (APS), as Outlined in the "Beyond Alternative Policy Scenario" (BAPS) for 2030 (after IEA 2006)

Because experience with implementing CCS has so far been insufficient, the APS deliberately omits it as a policy option. However, in its second scenario, the "Beyond Alternative Policy Scenario" (BAPS), the IEA does assign CCS greater significance as a kind of "supplementary technology", with a reduction potential of 2 Gt/a CO_2 (Figure 5). Implementing this additional measure could stabilise emissions at today's level by 2030.

The two scenarios considered so far show clearly that the general necessity and absolute and relative importance of the individual measures for climate protection depend decisively on the target set for reduction in CO_2 emissions. If we set even more ambitious goals — as would seem to be required to achieve the 2°C target — the options under consideration would have to deliver even greater contributions than in the two outlined scenarios.

3 CCS Technology Options

This chapter provides an overview of the various processes involved in CO_2 capture and storage, points out potential fields of application and describes the experience to date. Above all, the different storage options are elaborated, the available global and national storage potential is outlined and the importance of both assessed.

a. Possible Fields of Application of CCS

CCS can only sensibly be applied to large-scale point source emissions. Alongside the power generation as the classic application, this also applies to various industrial applications where carbon-based fuels are used to supply energy (e.g. the steel industry) or where chemicals (e.g. ammonia) or fuels are produced. In fact, in industrial applications the conditions may actually be considerably more favourable, because here CO_2 sometimes occurs in higher concentrations than in power generation flue gases (Table 1).

For the many decentralised CO_2 sources outside the power generation sector (e.g. cars, home heating systems) CCS is not from today's perspective available for direct application. But indirectly there is potential for CCS to make a contribution here too, through centralised production of low-carbon fuels, for example production of hydrogen (H_2) through coal gasification with CO_2 capture.

Type of plant	Typical CO_2-concentration in waste gas
Cement plants	15–25 percent
Iron- and steelworks	15–20 percent
Ammonia plants (waste gas)	8 percent
Ammonia plants (pure CO_2)	100 percent
Refineries	3–18 percent
Hydrogen production (waste gas)	8 percent
Hydrogen production (pure CO_2)	100 percent
Petrochemical plants	8–13 percent
Power stations (flue gas)	*3–15 percent*

Table 1:
Typical CO_2 Concentrations in Waste Gases in Various Processes (after ECOFYS 2004, *italics: our additions*)

b. CO_2 Capture Processes

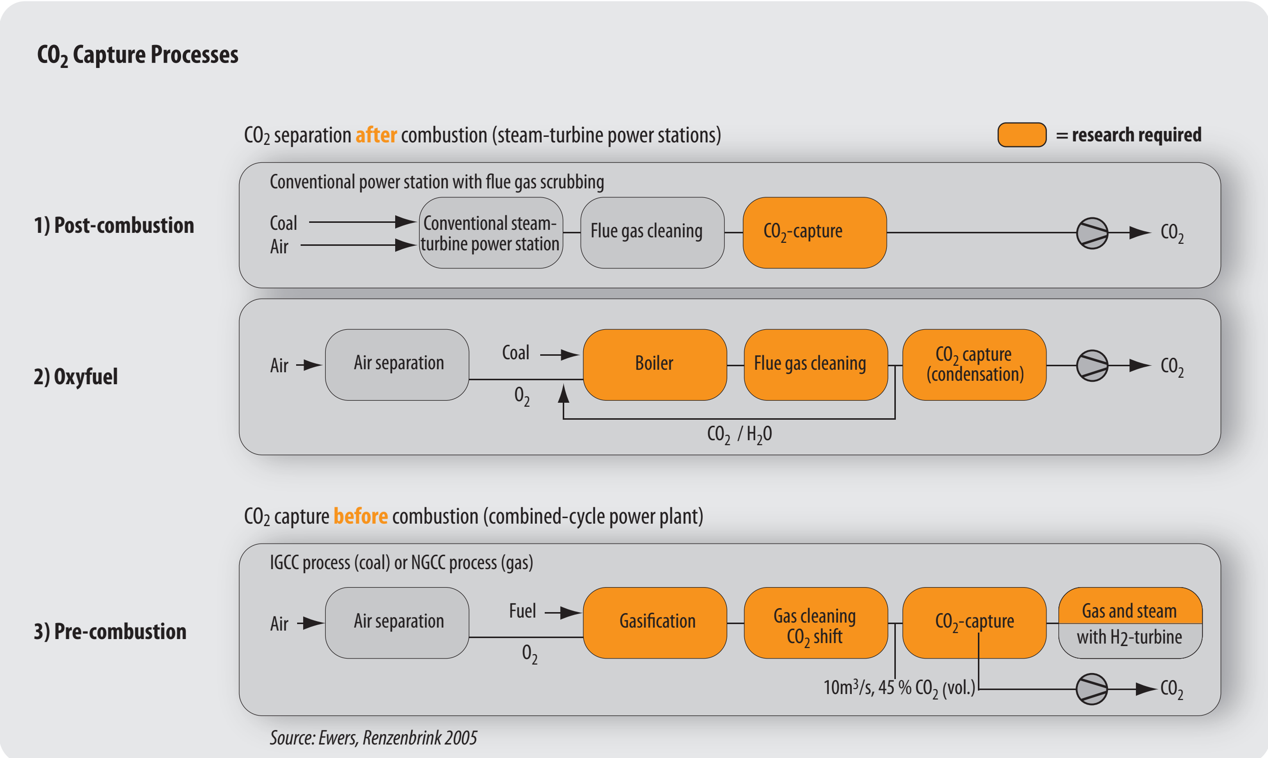
Plans for reducing CO_2 in electricity generation focus on coal-fired power stations, because in relative terms their specific CO_2 emissions are the highest. Accordingly, most demonstration projects are planned in this sector.

Although the technology for small-scale industrial CO_2 capture is already regarded as proven (especially in the chemicals industry), it cannot yet be bought "off the shelf" for use in power stations. Considerable development efforts are still needed, especially for upscaling (by a factor of 10 to power plant dimensions) and for reducing the energy required by the process itself. Therefore it is expected that large-scale CCS technology will not be available until 2020. From the technological point of view there are three options for CO_2 capture in the medium term (Figure 6).

Capturing CO_2 after combustion using chemical flue gas cleaning (post-combustion) is the most mature technology, but it is also relatively expensive, energy-intensive and space-consuming. Additionally, very large amounts of environmentally relevant chemical cleaning agents (e.g. monoethanolamine or MEA) are required for the flue gas treatment. As a downstream unit the process is in principle suitable for retrofitting conventional power stations.

The oxyfuel process, where coal is burnt in pure oxygen rather than in air, is currently still in the demonstration phase. The advantages of the oxyfuel process are minimised flue gas energy losses, minimised nitrogen oxide emissions and in particular easier separation (condensation) of the CO_2 from the other flue gases, because of the absence of atmospheric nitrogen in the flue gas. On the negative side, the amount of equipment and energy required is considerable because of the necessity to install air separation equipment.

Figure 6:
Overview of CO_2 Capture Processes



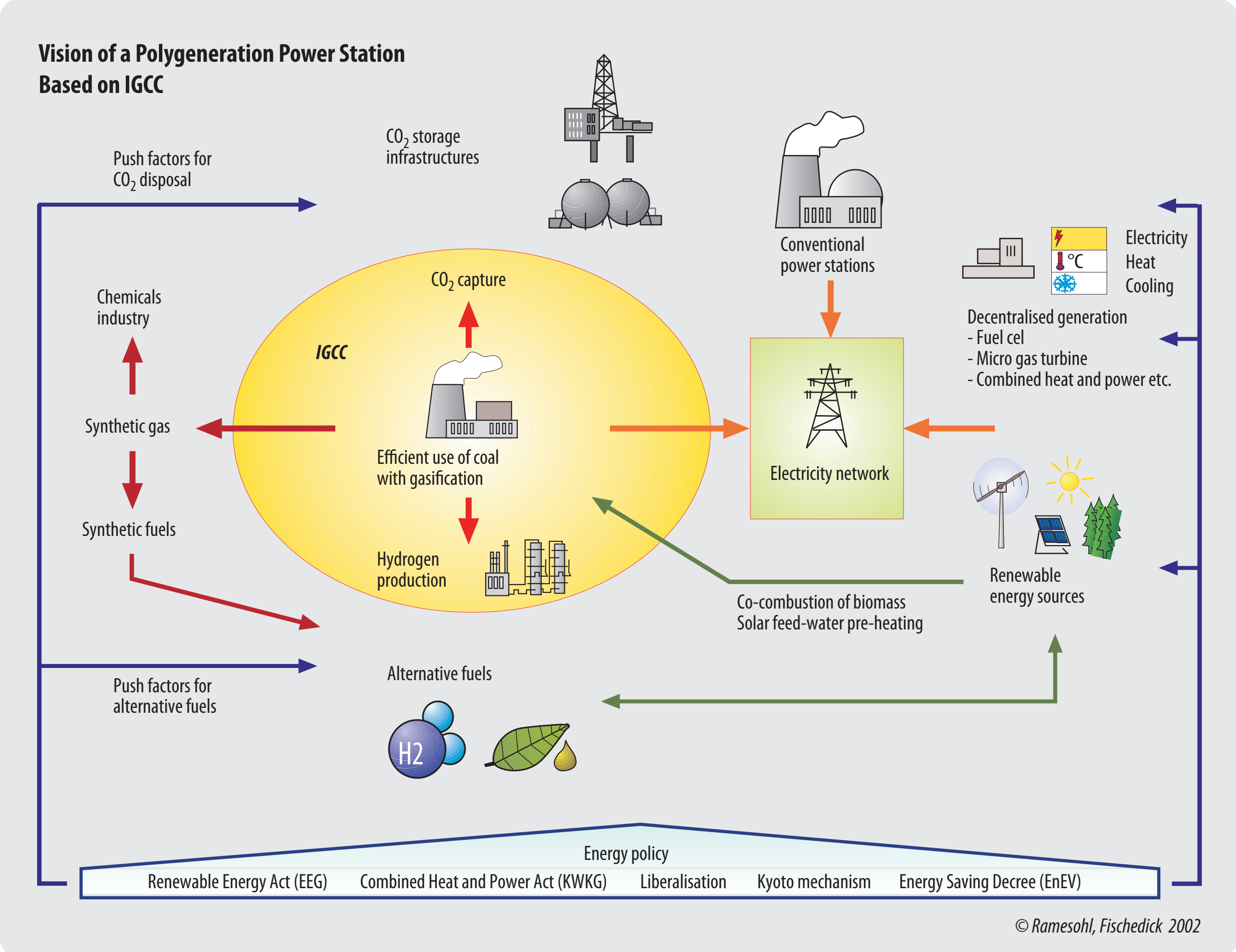


Figure 7:
Vision of a Polygeneration Power Station with Various Inputs and Outputs Based on Integrated Gasification Technology (IGCC)

Pre-combustion CO_2 capture in combined-cycle coal- or gas-fired power stations is more flexible than CO_2 flue gas separation but also a less technically mature process. The technologies are known as Integrated Gasification Combined Cycle (IGCC) for coal and Natural Gas Combined Cycle (NGCC) when natural gas is the fuel. In the first process coal is gasified in several stages to produce carbon dioxide and hydrogen (with natural gas the process is called reforming). The cleaned gas can be used to generate electricity extremely efficiently in a combined gas and steam turbine system. The main problem here is that the technology is not yet properly ready for application on the large power generation scale. Commercial experience with this technology has been gained to date at two European plants (Puertollano in Spain and Buggenum in the Netherlands) and in the United States.

In principle IGCC offers the possibility of great input and output flexibility. Apart from coal, for example, biomass and other special fuels can be also used in solid fuel gasification, and although the main product is electricity, the output portfolio is not restricted this. Depending on which subsequent process is applied (e.g. Fischer-Tropsch synthesis), the intermediate and final products can also be used to produce fuels (e.g. hydrogen, synthetic fuels). IGCC using CCS thus also allows a link to be made to the fuel industry (Figure 7).

As well as the three processes described here, a wide range of options are also at the development stage (e.g. improved air separation, hydrogen membrane technology, new power station concepts with integrated oxygen supply systems), which are aimed above all at reducing the energy consumed by the CCS process itself and cutting costs. However, implementation of these systems is only to be expected in the medium- to long-term.

c. CO_2 Transport and Infrastructure

Constructing the transport infrastructure will be a major factor in any future CCS regime. Questions of transport infrastructure play a major role in decisions affecting potential power station and storage locations. This is a classical optimisation problem, where the target parameters encompass minimising CO_2 transport, electricity transport, fuel transport, transport costs, and ecological and social impact. As well as transport, transit storage facilities may also be needed (Figure 8).

From the energy efficiency, economics and ecological perspective the only relevant options for large-scale CO_2 transport are pipelines (onshore and possibly offshore) and large tanker ships. To minimise the transport costs the CO_2 would be transported in its supercritical state.*

* In thermodynamics, "supercritical" describes a very dense state above the "critical point", where a clear distinction between the liquid and gaseous states is no longer possible.

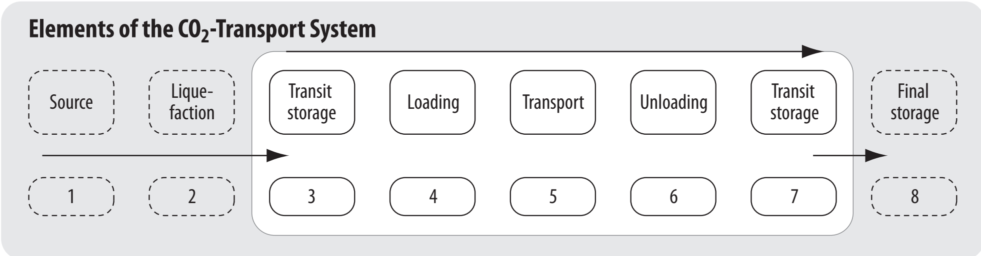


Figure 8:
Elements of the CO_2 Transport System (source: Schlattmann 2006)

Explanations:
1: Power generation
2: Required for CO_2 transport in liquid or supercritical state
3+7: Required for CO_2 transport with discontinuous discharge (lorry/rail/ship), not automatically needed for pipeline
8: Geological storage

Means of transport	Capacity	Seasonal availability	Cost in euro/t (250 km)	Necessary infrastructure already exists at source/ destination?	Comments
Ocean-going ship	< 50 Mt/a	Yes	< 1	Almost never	Generally requires multi-modal transport
Inland waterways	< 10 Mt/a	Seasonally restricted (water levels)	approx. 1	Partially	Inland vessels not sea-going, time restrictions
Pipeline	< 100 Mt/a	Yes	approx. 1.5 (depending on diameter)	Would almost always have to be constructed (large investment)	Service life 25 years, higher costs in built-up areas
Rail	< 1,2 Mt/a	Yes	approx. 5	Generally	Noise
Lorry	< 0,5 Mt/a	Restrictions in winter, congestion	approx. 25	Always	Cost, noise, emissions, time restrictions

Table 2:
Suitability of the Different Means of Transport for CO_2 and their Characteristics (source: Wuppertal Institut)

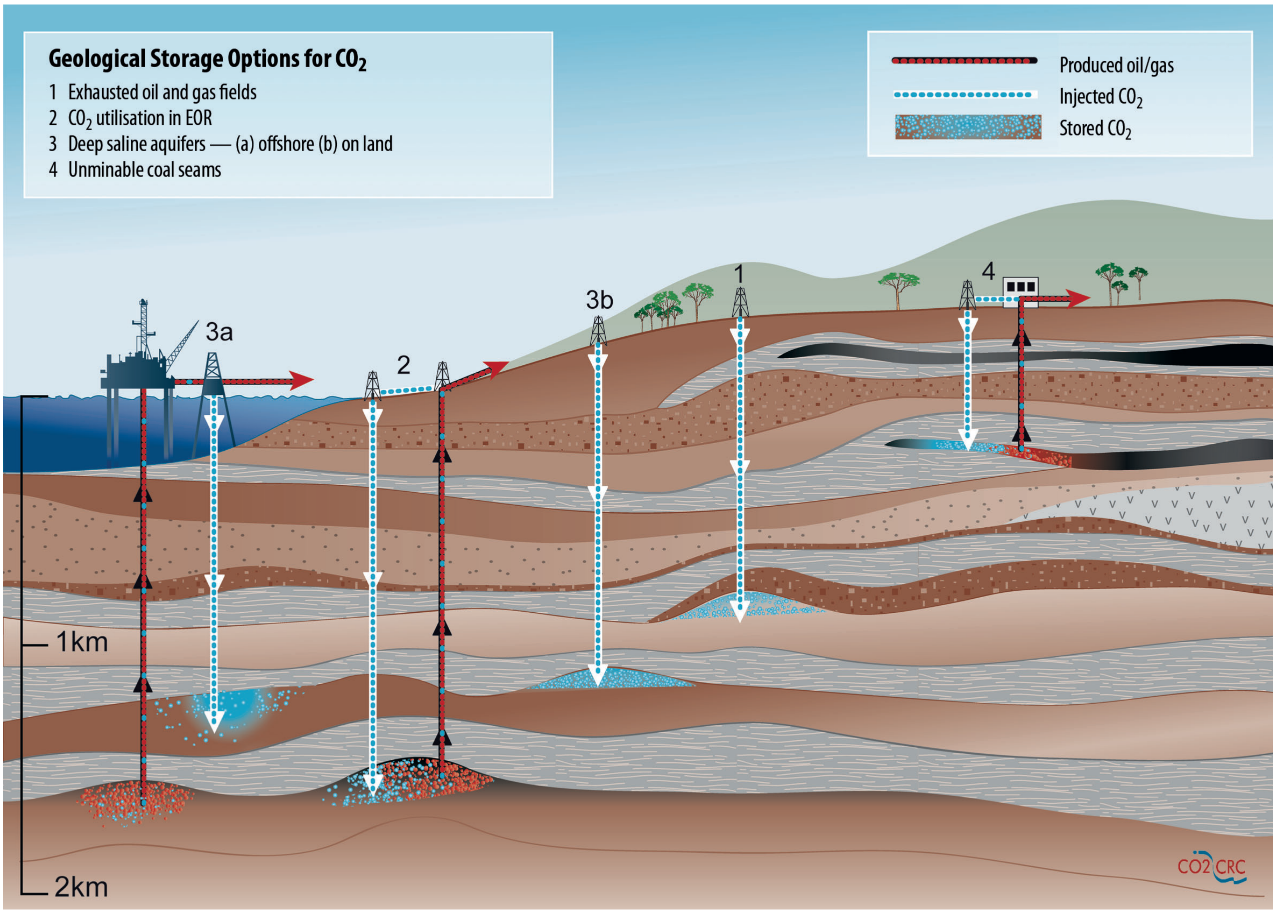


Figure 9:
Possible Geological CO_2 Storage Options (after IPCC 2005; graphic: CO2CRC)

One advantage of pipelines is that they can transport very large amounts of CO_2 continuously, with relatively little environmental impact and at acceptable operating costs. One disadvantage is that great investment has to be made in constructing new pipeline infrastructure. Ships, on the other hand, can be deployed more flexibly and are available more quickly, but require transit storage and loading/unloading infrastructure, and depending on the location will generally call for multi-modal transport (Table 2).

d. Options and Potentials for CO_2 Storage

From the ecological and economic perspectives, storage in geological formations (e.g. exhausted oil and gas fields, saline aquifers and potentially also deep unmineable coal seams) is currently the most attractive option (Figure 9). One special case is represented by Enhanced Oil Recovery (EOR), which involves using CO_2 to increase the recovery rate of oil fields (see text box p.16).

In contrast to geological storage, industrial utilisation (e.g. production of carbonic acid, dry ice, raw materials for polymer chemistry) will only be possible on a small scale. Furthermore, in these cases the CO_2 is not removed for ever from the atmosphere but in fact released again at a later date. A net effect here is only achieved if the CO_2 used replaces technical production and supply of CO_2 (i.e. specially for the industrial purpose) elsewhere.

Enhanced Oil Recovery (EOR)

In crude oil extraction, numerous different techniques are used to increase the yield. One of these is the injection of CO_2. The injected CO_2 increases the pressure in the reservoir and diffuses into the crude oil, making it more fluid and therefore easier to extract. So by using CO_2 for EOR the oil yield can be increased (which generates revenue) and at the same time carbon dioxide can be permanently transferred into geological formations and so be removed from the atmosphere. The latter applies at least to the portion of the CO_2 that is not mixed with the oil.

Owing to the economic incentives CO_2 EOR is often regarded as an attractive way to begin using CCS. But EOR only generates additional profits in those places where it is possible to establish a cost-effective infrastructure (short pipeline distances, etc.). Enhanced oil recovery through carbon dioxide injection is already being used at various places across the world (e.g. the Weyburn oil field in Canada) and can be regarded as an established technology. On the other hand, there has been no practical experience with the analogous process of Enhanced Gas Recovery (EGR), for which to date there has only been work on simulations.

The idea of binding CO_2 in the marine environment either directly (storage in the ocean depths) or indirectly (e.g. algae formation) is currently being pursued only sporadically (mainly in Japan) due to public opposition (the question of permanence of storage, insufficient knowledge of the effects on marine ecosystems) and low efficiency. CO_2 can also be fixed through the deliberate cultivation of biomass (e.g. through forest planting, although this stores CO_2 for only a few decades). Additionally, especially in the United States, processes for binding CO_2 to silicates (mineralisation) are being discussed, but the high energy requirements and large amounts of material to be disposed of are discouraging.

This means that from today's perspective the geological storage options are clearly the most realistic ones. Owing to the many uncertainties involved, current estimates of storage potential differ enormously. Ultimately, a case-by-case assessment will be required if we are to gain insights into storage capacity. IPCC estimates put global storage capacity at between 1,678 and 11,100 Gt CO_2, with 2,000 Gt CO_2 classed as technically viable (IPCC 2005). By way of comparison, global CO_2 emissions in 2005 amounted to 27.3 Gt CO_2.

Total storage capacity for Germany (with annual emissions of about 0.86 Gt CO_2) is estimated to be between 19 and 48 Gt CO_2 (Table 3). Concentrating on the particularly promising storage options of exhausted gas fields and saline aquifers (which together offer a potential of between 14.3 and 30.5 Gt CO_2) gives a calculated static range of CO_2 storage in Germany of between 28 and 60 years. This calculation relates to the point source CO_2 emissions in Germany (in 2005: 393 Mt/a) and takes into account an average extra energy requirement of 30 percent for capture.

The storage possibilities in Germany are geographically very unevenly distributed. Favourable conditions are found above all in the North German Basin and thus at sometimes considerable distances from the major point sources (especially the power stations), which are currently concentrated in the Rhineland, the northern Ruhr region and the Lusatia region. Significant storage capacities may also be found outside Germany, for example through cooperation with the Netherlands with its large natural gas fields.

Option	Capacity in [Gt]	Long-term stability	Cost*	State of the art	Use conflicts	General risks
Exhausted gas fields	+ 2,3–2,5**	+	+	+ (+)	–	+
Deep saline aquifers	+ + 12–28**	+	– –	+	–	(+)
Deep coal seams	+ (+) 3,7–16,7	+	– –	–	–	–
Exhausted oil fields	– – 0,11	+	+ +	+ +	–	+
Salt mines	– – 0,04	– –	n.a.	+	– –	– –
Closed coal mines	+ 0,78	– –	– –	– –	– –	–

Table 3:
Assessment of Geological Storage Options in Germany Using Selected Criteria (source: Wuppertal Institut)

* The cost assessment covers only storage costs, without capture, compression and transport (after ECOFYS 2004, BGR, our additions)

** Figures after May et al. 2005

Key:
– – Negative or very problematic
– Fundamental difficulties still exist, but may be solvable
\+ Good, or small obstacles
\+ + Very good
() Parentheses indicate uncertainties or necessity for case-by-case examination
n.a. Not available

In principle the storage of CO_2 in geological formations can be accomplished through many processes and technologies already used in the oil and gas industry and in handling liquid wastes. Drilling and injection processes, monitoring methods and computer simulations about the distribution of the CO_2 in the reservoir would, however, have to be adapted to the specific requirements of CO_2 storage. Here there is still a considerable need for research and development. The EU-funded CO2SINK project at Ketzin near Berlin is contributing to resolving these questions through its research into the behaviour and controllability of CO_2 in underground reservoirs (see www.CO2sink.org).

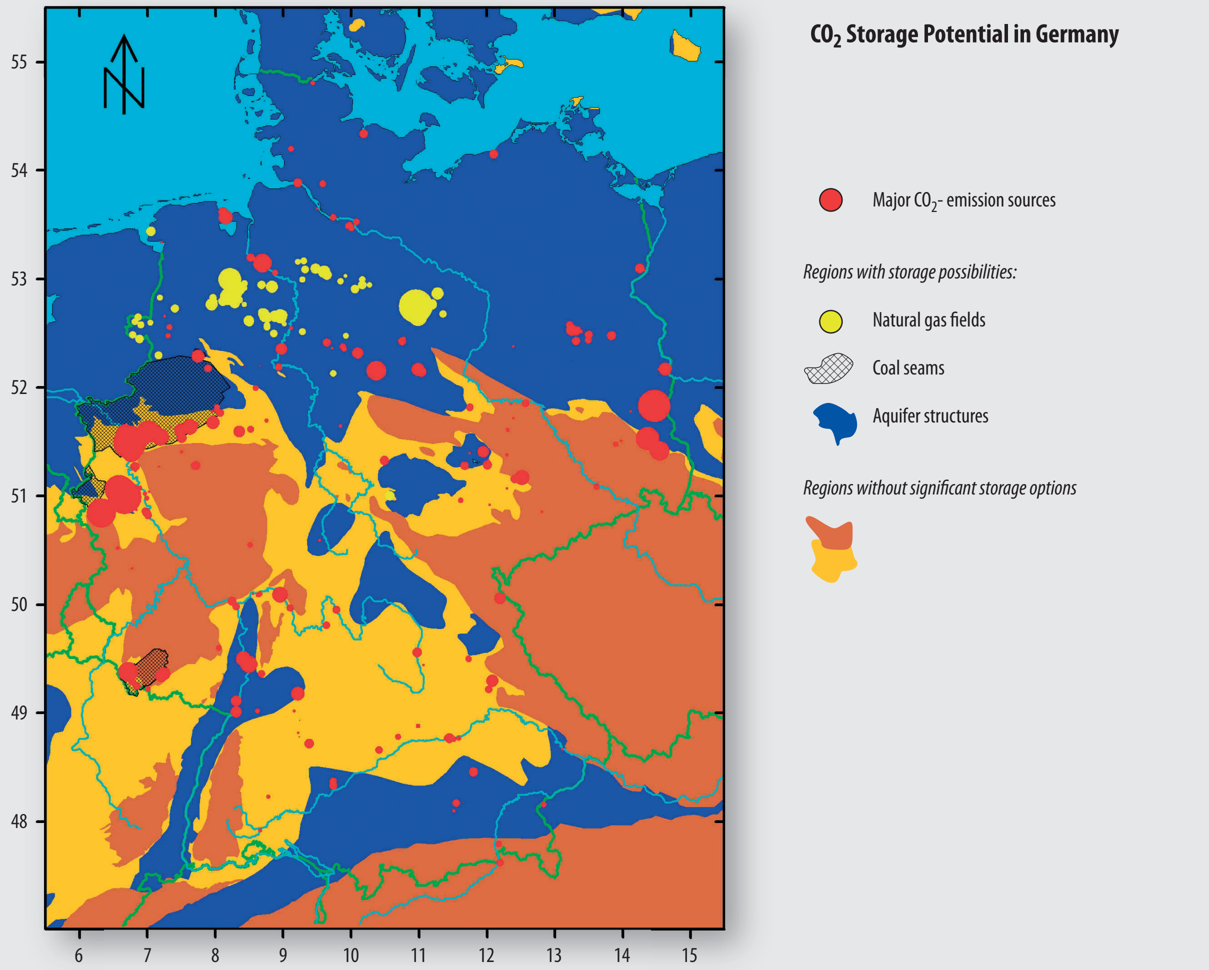


Figure 10:
CO_2 Storage Potential in Germany and its Geographical Distribution (source: BGR)

e. Experience to Date with CCS

To date large-scale technical experience with storing CO_2 has been gained in various countries. In the United States natural CO_2 has been injected into oil reservoirs deposits to improve recovery since the 1970s. About 35 Mt CO_2 are stored annually, distributed through a pipeline network with a total length of about 3,000 kilometres. In the Weyburn oil field in Canada, too, CO_2 has served the purpose of enhanced oil recovery (EOR) since 2000. The CO_2 originates from a coal gasification plant in North Dakota (United States), is supplied through a pipeline system, and after injection remains in the empty oil field (about 1.8 Mt CO_2 are stored each year, the total storage capacity is said to amount to approx. 20 Mt CO_2.

CO_2 storage is also a long-standing practice in Norway, where since 1996 — initiated not least by the introduction of a tax on CO_2 emissions — CO_2 has been separated in the Sleipner gas field (offshore) and 1 Mt CO_2 has been stored annually in a saline aquifer above the gas field. Since 2007, the CO_2 extracted together with the natural gas from the Norwegian Snohvit gas

Figure 11:
Experience with CO_2 Transport and Storage in the United States and Canada (after IPCC 2005)

field has also been stored in an aquifer. At the In Salah gas field in Algeria the CO_2 produced together with the natural gas has been stored in an empty gas field since 2004. The storage reservoir is believed to have a total capacity of 17 Mt CO_2. The annual storage rate is 1.2 Mt/a.

Numerous other CCS projects (especially demonstration and research projects) are in planning and will play a decisive role for the further development of the technology over the coming 10 to 20 years. They will show whether CCS can fulfil the necessary technical, economic and ecological requirements for its large-scale use and what role CCS can play in national and international energy systems.

4 Technical, Economic and Ecological Preconditions for the Success of CCS

Chapter 4 describes the technical, economic and ecological preconditions for implementing CCS in practice (the necessary factors for success), showing how CCS can be integrated in the existing energy systems and also how open questions concerning the implementation of CCS can be resolved.

a. Long-term Permanence of Storage

To ensure secure storage of carbon dioxide only reservoirs that have suitable covering strata should be chosen. This is necessary in order to ensure that CO_2 rising through leakages (fractures in the rock formation, and similar) can be stopped by multiple barriers. Favourable preconditions for stable storage are particular geological formations known as stratigraphic and structural traps (case A in Figure 12). Here the injected CO_2 is contained vertically and laterally by the enclosing formation. Where there is only a stratigraphic trap the injected CO_2 can in principle move laterally underneath the covering formation.

Alongside containment of CO_2 in the pore volume through structural and stratigraphic traps various other temporal processes also ensure that CO_2 can remain in the storage formation. Part of the CO_2 dissolves in the saline interstitial water. No longer existing as an independent phase, it can no longer be driven out, owing to the lack of buoyancy. In the next step, specific ions form and in the long term mineralisation of at least part of the CO_2 can occur (carbonate formation). Mineralisation leads to permanent containment of the CO_2, but this process can take 1,000 years and more and may only involve part of the CO_2.

In practice the selection of suitable storage locations calls for a dedicated risk analysis and risk management. The risk analysis must identify, classify and evaluate all the possible factors that could influence the safety of the store. Scenarios are used to assess which events might occur that would lead to leaks. Risk assessment involves deterministic approaches as far as possible. However, owing to uncertainties involving various parameters (e.g. permeability of structures) probability estimates are also carried out. Risk management takes the results of

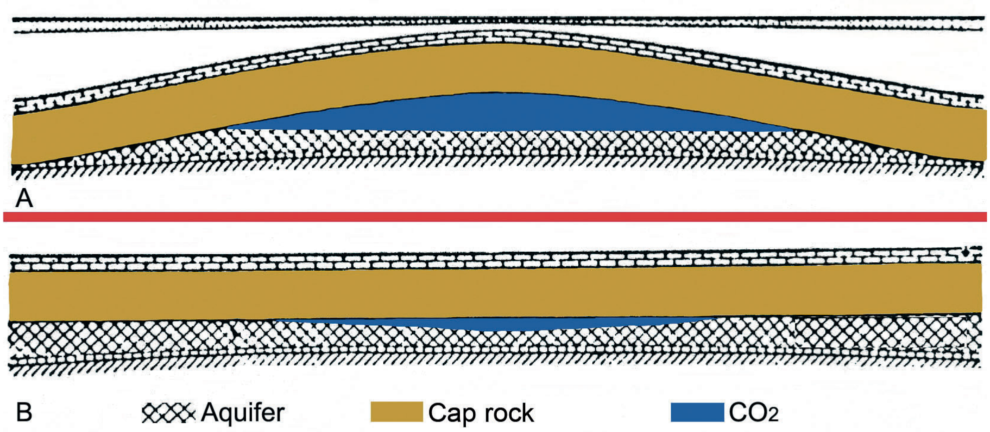


Figure 12:
Geological Preconditions for Stable Storage
Case A: Stratigraphic and structural trap
Case B: Structural trap
(source: WI/GD 2006)

risk analysis and attempts to translate them into practical measures, e.g. the careful selection of storage locations and precautionary measures for preventing leakage risks.

If we assume that storage locations are selected accordingly, the IPCC estimates that the percentage of the CO_2 remaining in the storage location after 100 years will with high probability still amount to 99 percent (IPCC 2005). Even after 1,000 years it is still considered probable that 99 percent of the stored CO_2 will remain contained. Here the IPCC designates a probability of between 90 and 99 percent as "highly probable" and a probability of between 66 and 90 percent as "probable". In its critical examination of CCS the German Environment Agency calls for the maximum annual leakage rate not to exceed 0.01 percent. Purely arithmetically, that would mean that after 1,000 years 90.5 percent of the originally stored CO_2 would still be in the store (UBA 2006).

b. Economic Viability

On the cost side, CCS has to compete with other climate protection options. Today the step of CO_2 capture is the cost-determining factor within the CCS process chain. An evaluation of 17 case studies from seven European countries conducted as part of the GESTCO project* finds capture accounting for more than 60 percent of the average overall cost of 54 EUR/tCO_2 calculated from all the cases studied (Figure 13). For certain industrial chemical applications — especially ammonia and hydrogen production — the capture costs can be significantly lower. The overall range of CO_2 avoidance costs through CCS vary widely owing to the broad spectrum of different applications, as the IEA estimates in Table 4 clearly illustrate. Whereas certain EOR projects recoup net returns of up to 40 EUR/tCO_2 through CO_2 injection, in less favourable constellations (e.g. smaller non-EOR projects with longer transport distances) it may be necessary to invest up to 100 EUR/tCO_2.

The goal of ongoing research, demonstration and pilot projects is to significantly reduce the costs to allow CCS to become a competitive climate protection option. In the electricity generation sector the industry strives for additional costs for the whole process chain (i.e. including transport and storage) not exceeding 20 EUR/tCO_2.

* The investigation covered six different plant types (natural gas and steam, coal-fired power station, H_2 production, gas-fired power station, oil refinery, NH_3 production) for four different products (electricity, oil, NH_3, H_2) with three different capture processes (post-combustion, pre-combustion, pure CO_2 sources) and three different storage options (aquifer, oil/gas fields, coal seams).

Distribution of CCS Costs

Evaluation of 17 European Case Studies
Mean total cost: 54.00 EUR/tCO_2

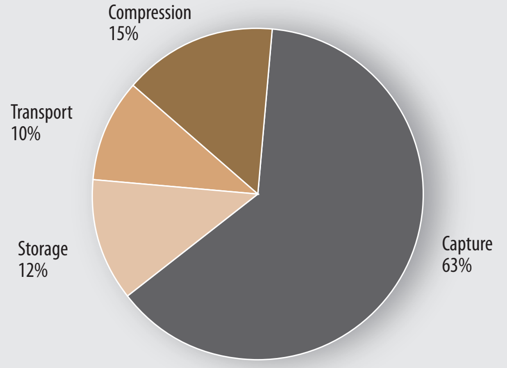


Figure 13:
Distribution of Average CCS Costs for Capture, Compression, Transport and Storage from the GESTCO Project (after GESTCO 2004)

Table 4:
Bandwidth of CO_2 Avoidance Costs (source: IEA 2004)

	Cost [US$/t CO_2]	Uncertainties
CO_2 capture (incl. compression)	5 – 50 (today) 5 – 30 (future)	Lower estimate for pure gas flows that merely have to be compressed; upper estimate for chemical flue gas scrubbing in gas and steam power
CO_2-transport	2 – 20	Dependent on transport capacity and distance
CO_2-storage	2 – 50	Lower estimate for aquifer storage in megatonne range; upper estimate for particular ECBM projects
CO_2-EOR (onshore)	-55 – 0	Potential revenues from EOR projects
Total	-46 – 120	

c. Ecological Compatibility

With regard to ecological compatibility, apart from the potential dangers through release of CO_2, the main factor that should be pointed out is the large energy requirement for CO_2 capture. This brings with it a significant reduction in efficiency, which in the power station sector can amount to 8 to 10 percentage points and more (which means an increased fuel consumption of up to 30 percent). For this reason CO_2 capture only makes sense in power plants that have a high output efficiency. It must be a goal to introduce technological improvements to reduce as far as possible the energy required for capture and the associated environmental effects.

Figure 14:
Greenhouse Gas Reductions and Residual Emissions after CO_2 Capture and Storage in CO_2 Equivalent (after Wuppertal Institut et al. 2007).

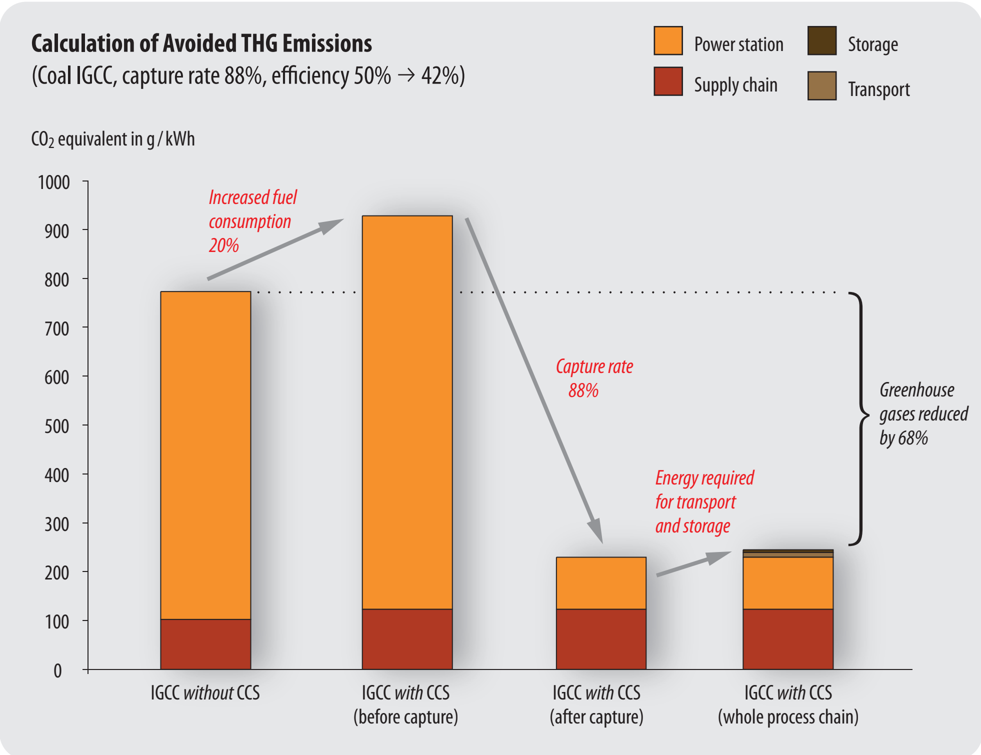


Figure 14 summarises the capture rates that can be achieved across the whole CCS process chain, taking the example of a modern coal-fired power station. If we assume a currently typical CO_2 capture rate in the power station of 88 percent, the potential CO_2 reduction is 78 percent over the entire process (including the fuel supply chain). In this context the designation "CO_2-free" power station is misleading; "low CO_2" would be more appropriate, even if in future it will be possible to increase still further the capture rate in the power station. If we take the whole spectrum of greenhouse gas emissions into consideration (i.e. especially the CH_4 or mine gas that is released during coal mining), a reduction of 68 percent is found for the example considered here.

d. System Compatibility

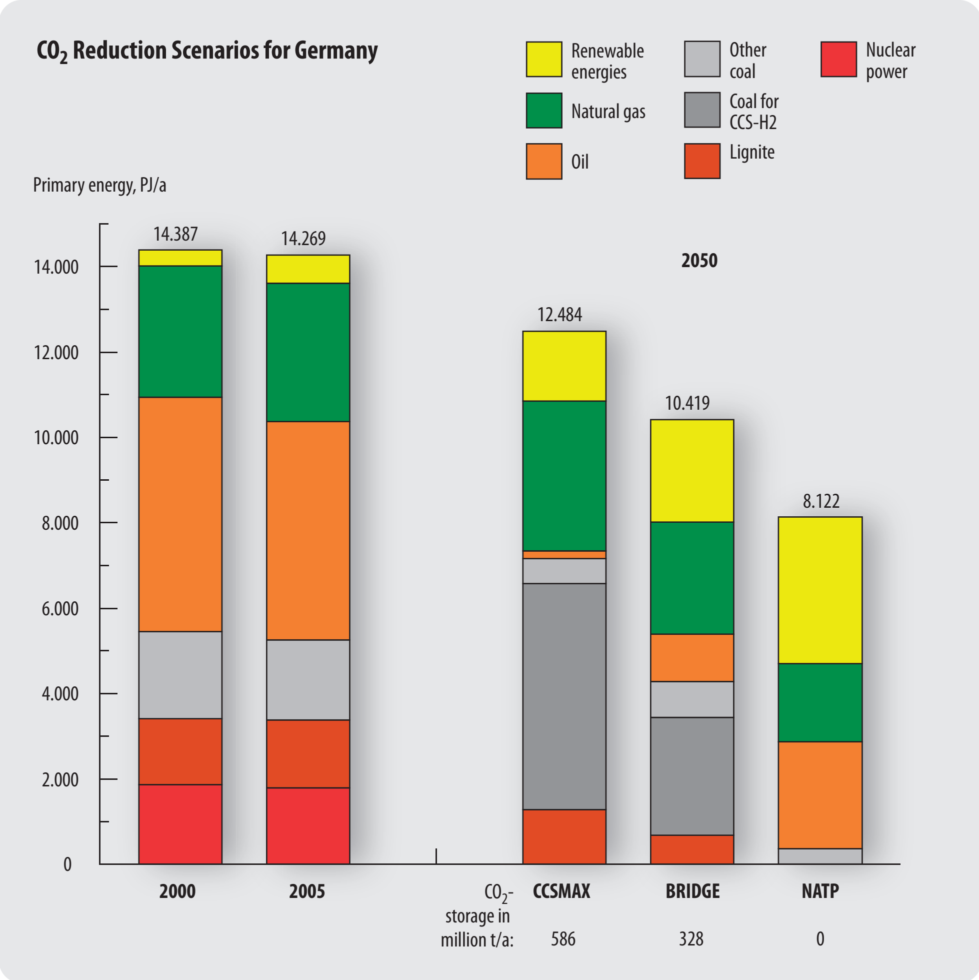
Decisions about implementing CCS depend not only on technical and economic questions and the institutional and social framework, but also on energy-structural aspects. System compatibility and harmonisation with other climate protection strategies represent significant preconditions for introduction. Seen from today, there would appear to be almost no negative interactions with other climate protection strategies, apart from a potential user conflict with deep geothermal energy production. However, there are climate protection measures in which CCS does not come to bear, e.g. in the expansion of decentralised combined heat and power. Yet since CCS significantly increases the cost of using fossil fuels, it could help boost the attractiveness of other climate protection strategies such as increasing efficiency or expanding renewable energies. From the climate protection perspective, CCS allows for the first time a cost comparison on almost equal terms, where the costs of CO_2 are included in full. Finally, CCS can also be combined directly with other climate protection measures, for example with biomass gasification, where it would contribute to producing a double dividend.

e. The Bridging Function of CCS

The existing scenario analyses for Germany show that, given a commitment to climate protection targets, CCS could today primarily fulfil a bridging function for the transition to an energy economy characterised by renewable energies. There seems to be no question that a long-term sustainable energy supply can only be formed from renewable energies in combination with greatly increased efficiency in the use of energy, owing to the limited reserves of fossil fuels (and CCS actually requires additional fuel consumption) as well as the limited CO_2 storage potential. But CCS could be a valuable additional technological option if it turns out that the expansion of renewable energies is delayed and implementation of large-scale energy saving options that are profitable in macroeconomic terms cannot proceed as desired owing to resistance and obstacles put up by various actors and the associated conflicts of interests. Figure 15 illustrates such a scenario (BRIDGE scenario). Compared to the NATP scenario it manages with a slower pace of expansion of renewable energies and also requires a lower rate of exploitation of energy saving potential. In comparison to a scenario based on maximum CCS (CCSMAX scenario), significantly less CO_2 has to be stored, which would make practical implementation appear a more realistic proposition (in 2050 the figures would be 328 and 586 Mt CO_2/a respectively).

A systems analysis of CCS must take into consideration that the technology is not expected to be available for large-scale implementation in power stations before 2020. In view of the power station replacement programme that is due to be implemented in Germany before 2020, the possibilities of retrofitting (possibly for only part of the flue gas flow) should be carefully analysed – alongside the option of building new power stations with integrated CO_2

Figure 15:
CO_2 Reduction Scenarios for Germany (Target: 80 per-cent reduction 1990–2050) (source: Wuppertal Institut et al. 2007)



capture – and included as far as possible in today's investment decisions (through a "capture ready" design). In terms of energy economics, the large amount of extra energy required for the CCS system itself means that retrofitting only makes sense in power stations that are sufficiently efficient. CCS must always be seen in combination with maximum efforts to increase the overall efficiency of the plants.

Moving away from Germany, a brief glance at China shows the potential importance of CCS on the global scale. Here too, CCS can fulfil a bridging function. According to the IEA, China is currently planning to build 20 to 25 GW of coal-fired power station output every year (IEA 2004). That annual increase corresponds to three-quarters of the total installed capacity of coal-fired power stations in Germany.

5 The Institutional Framework for CCS Technology

CCS is a new set of technologies for which no institutional framework has yet been tailored. By institutional framework we mean the legal aspects and regulatory conditions. Of particular importance — not least for public acceptance — are clear rules regarding long-term liability for the risks associated with storage. Sufficient economic incentives will be required for CCS to find its way into the market. Here the integration of CCS in the Kyoto instruments has a special role to play. For investors, legal security is always an important decision-making factor, alongside the economic perspective.

a. The General Legal Framework

The requirements for regulation are very diverse. The text box below provides a concise overview. Certain special aspects are then dealt with in greater detail in the following. Legal questions are dependent on the structure of the state systems involved. Clarification is therefore required at three levels — international, regional (e.g. EU) and national — with complementary solutions that take into consideration the differing conditions in the different regions and nation-states.

For the discussion on regulatory requirements concerning CCS it is necessary to distinguish between the individual steps of the process: capture, transport and storage. For legal purposes (e.g. waste disposal or mining law) even the terms chosen can be decisive. For example, whether one speaks of "storing", "depositing" or "dumping" can have very different legal implications. The same applies to public perception of the technology, which also draws strongly

Goals of Regulation

- Clear legal classification of the various steps of the process.
- Consistency and compatibility between the international legal framework and the relevant national frameworks.
- Criteria for selecting suitable storage sites.
- Planning and legal security for all involved, through clear and transparent regulation of responsibilities (including liability) and rights.
- Involvement of relevant actors in defining the regulatory process as part of a suitable consultation process.
- Inclusion of procedures for risk assessment and risk management in the approval process.
- Monitoring and reporting on all stages of the process (CO_2 capture, transport, storage) in agreement with the CCS-specific "2006 IPCC Guidelines on Greenhouse Gas Inventories" for a sufficient period (e.g. for the duration of the emissions trading system).

on concepts and analogies associated with the legal classification. Accordingly, the literature on regulatory matters presents widely differing perspectives that are determined by the choice of terms. For example, "storing" suggests that waste disposal law has no role to play, whereas "dumping" implies the exact opposite. The following individual fields of law have a bearing on CCS, and accordingly the development of CCS will need to take account of the protection regulations in these fields.

- Capture is subject principally to national law. In Germany this is first and foremost anti-pollution law. The approval procedure under anti-pollution law has a concentrating effect and includes other fields of law (soil protection, water, waste, nature protection and environmental compatibility). Given that the capture equipment itself is ancillary to the power station process, a fundamental reform of the anti-pollution law would appear unnecessary. What is, however, unclear, is the question of how to classify the product of capture, the CO_2 — as waste, as a by-product or as an emission. The rules valid today often include no suitable category for the CO_2 captured from flue gases. For example, German waste disposal law does not cover gaseous materials that cannot be stored in containers (e.g. drums). Legal security on these aspects is important for all actors.
- For transport applicable law on whether final storage is to be in Germany or elsewhere (in particular under the sea bed) and transport by ship is accordingly to be part of the logistics chain. For the application of transport law it is also important to clarify whether the captured CO_2 (and the accompanying gases) are to be classified as coming under waste law.
- For storage, the fields of law relating to deposition under the seabed have been relatively thoroughly studied. The relevant instruments are the United Nations Convention on the Law of the Sea (UNCLOS), the London Protocol (to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter), the OSPAR Convention (for the Protection of the Marine Environment of the North-East Atlantic) and HELCOM (the Baltic Marine Environment Commission). The Contracting Parties to the London Protocol adopted in 2006 an amendment which allows for carbon dioxide capture in sub-seabed formations. With the amendment ‚carbon dioxide streams from carbon dioxide capture processes' can be stored if they meet three criteria: 1. disposal is into a sub-seabed geological formation, 2. the carbon dioxide stream is of high purity; and 3. no waste is added for the purpose of disposal. The changes to the London Protocol will likely lead to an amendment of the OSPAR Convention to provide explict legal guidance on CCS. In fact, this process has started earlier this year and some progress has been made.

The main field of law pertaining to storage on national territory (in Germany) is mining law. This is due to the fundamental comparability with natural gas storage (even if the purposes of storage are different: with natural gas storage the goal is later use, while CO_2 storage is about the safest possible permanent storage). But this will be in a context of congruence or conflict with waste disposal and anti-pollution law, depending on the classification given to CO_2. Water protection law (for injection into aquifers) and soil protection law may also be applicable.

b. Specific Questions of Legal Liability

Transparent and plausible clarification of questions of legal liability is of key importance, especially with regard to public acceptance of CO_2 storage. Fundamentally, the operator is responsible for risks and damage resulting from his activities (here storage of CO_2 and risks subsequently presented by the CO_2). It is, however, currently unclear to what extent this responsibility extends to the period after the end of the storage process. Permanent openended liability is impossible simply for practical reasons, so ultimately there is no alternative to state liability. However, there should also be a suitable form of private risk provision in order to keep the potential burden on the state as small as possible. The decision on the duration of private legal liability and the point at which responsibility passes to the public domain must be made pragmatically. According to existing proposals this could be a period of 30 years after the end of the injection process (Öko-Institut 2007).

Liability rules are needed not only for the national level, but also in the international context, to the extent that the CO_2 is transported across international borders. The responsibilities here must be regulated in the aforementioned treaties and agreements.

As well as legal clarification of questions of liability, other proposals are also under discussion, for example to ensure prudent selection of storage sites by issuing bonds (Edenhofer 2004). The same also applies to the formation of financial reserves. Here, for example, analogies could be drawn with lignite mining (escrow funds for regenerating the mined area).

c. CCS and Kyoto Instruments

For the deployment of CCS, economic incentives provided by existing climate protection agreements or through the existing national and international mechanisms are essential. The European Emission Trading Scheme and the Clean Development Mechanism (CDM)* are of central importance here. The latter is decisive in the sense that it provides economic incentives to deploy CCS in countries with steeply rising CO_2 emissions, such as China and India.

* The CDM covers project-like measures to reduce greenhouse gases in a state that is not yet obliged to reduce greenhouse gases (under the Kyoto Protocol) that are conducted by a state that is subject to Kyoto obligations (or a company from that state), whereby the latter state can have the achieved reduction fully or partially credited.

EU Emission Trading Scheme (EU ETS)

The European Emission Trading Scheme focuses on large CO_2-emitting installations. If in future such an installation is retrofitted with a CO_2 capture system it will as a result emit significantly less CO_2 into the atmosphere. So one might think that CCS is quasi-automatically integrated into the EU Emission Trading Scheme, and that there is therefore no need to adapt the emissions trading regulatory system.

In reality, however, the CO_2 emissions from installations are not measured. In fact, the determination of CO_2 emissions is operationalised in an indirect way and defined in the Monitoring and Reporting Guidelines of the UNFCC as well as, in the same manner, of the EU. The fuel supplied to an installation is determined and on that basis the emissions to the atmosphere are calculated on the assumption that the total carbon content of the fuel is oxidised and released into the atmosphere in the customary way.

If CO_2 capture technologies are introduced into such an accounting system, then a fundamental change in the guiding philosophy for determining CO_2 emissions is required. The process of altering the accounting rules accordingly has been completed at the IPCC level with the drafting of corresponding guidelines (see text box p.28). The EU Commission is preparing a CCS Directive that is scheduled to be ready in mid-2007. The directive also covers the proposal to allow the respective authorised bodies to issue "Site Permissions" for storage sites, which would be the precondition for participation in emissions trading.

The discussion is not solely about correcting the emission value at the installation (currently handled as a gross value), or in other words the part of the CCS chain where capture takes place. The other steps in the process, transport and final storage, will also become new (potential) emissions sources and must be included in the monitoring system as such. Here there is a need to decide whether emissions from these elements should be treated as a part of the original emitting plant (virtually joined via CCS) or as completely independent isolated production processes. The existing system of EU emission trading makes a regulatory distinction between large point sources (as participants in the EU Emission Trade System or ETS) and

Provisions for CCS in the IPCC Guidelines

The IPCC is responsible for the methodology for determining greenhouse gas emissions from the respective state UNFCCC territories. It standardises the reporting procedure in its "Monitoring Guidelines". In April 2006 in Port Louis (Mauritius) the IPCC adopted the second revision of these guidelines, under the title "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (IPCC 2006). They include the treatment of CCS (Volume 2, Chapter 5). So important structural decisions have been taken that will shape the reporting systems of subsidiary territorial bodies such as the EU.

Structurally there were two options to choose between: accounting for CCS according to the "source" approach or according to the "sink" approach. The latter would have meant norming disposal of CO_2 analogously to the treatment of biological sinks. The IPCC chose the "source" approach. The three process steps are regarded as independent (potential) sources — just as also the emissions in crude oil extraction and transport to the refinery are not assigned to the production of fuel in a refinery.

The specific and most problematic point is storage. Here the IPCC has decided initially only to provide for "geological storage". Four types are listed:

- CO_2 storage in saline aquifers,
- CCS in connection with Enhanced Oil Recovery (EOR),
- Enhanced Gas Recovery (EGR),
- Enhanced Coal-Bed Methane Recovery (ECBM).

Furthermore, the IPCC has decided that emissions from the storage site must be measured and reported. The Guidelines give clear information about how this could be conducted. For further information see www.ipcc-nggip.iges.or.jp.

the various other smaller sources. All the problems that arise through cross-border transport of captured CO_2 (with accompanying gases) will also have to be solved.

Clean Development Mechanism and Joint Implementation

The question of whether CCS is suitable to be admitted as a CDM project is currently in the decision phase. A first "test balloon" is currently before the CDM Executive Board, giving the board reason to put the question to the responsible organs, i.e. the conference of UNFCCC treaty states (COP/MOP*). The responsible working group then discussed the issue at Montreal (2005) and arranged for a workshop in May 2006 attended by the member states. The outcome of this event can be summarised as follows:

* COP (Conference of the Parties to the Convention), MOP (Meeting of the Parties to the Protocol): Since the Kyoto Protocol came into force the regular meetings have been referred to as COP/MOP.

As a project type CCS invites series of methodological, political and legal problems, for example defining the boundaries of the project, treatment of leakages, the permanence of storage and the question of who bears responsibility for storage after expiry of the credit period. In a recent report (IEA 2007) the International Energy Agency described how CCS could in principle be integrated in the CDM.

The EU, Canada, China, India, Japan, South Africa and especially the OECD states expressly favour the use of CCS in the CDM framework. The EU and a number of other states also point to as yet unresolved problems that would have to be dealt with before implementation. The LDCs (Least Developed Countries), the Alliance of Small Island States (AOSIS) and Brazil voiced considerable reservations regarding the suitability and maturity of CCS. The delegates agreed to a further two-year negotiating process in the Subsidiary Body for Scientific and Technological Advice (SBSTA). COP/MOP 4 (2008) is to make a final decision on CCS.

Alongside the rather technical/methodological discussion outlined above, there is a second more general debate, asking to what extent the CDM is at all adequate for the CCS technology, because as a mechanism it was really introduced to support smaller projects.

d. Social Acceptance

Public debate and opinion-forming on CCS is still in its early stages. Up to now, only very few people are aware of the existence of these technologies. Positioning so far has largely taken place at the level of non-governmental organisations, political parties, industry and others. And at this level the application of CCS is definitely controversial in Germany. The environmental non-governmental organisations (ENGO), especially, have sometimes voiced considerable reservations, whereas politicians and industry are with some exceptions positive about CCS. German ENGOs would primarily like to see greater use of renewable energies and a significant increase in energy efficiency as the climate protection strategy of choice. They see the fundamental danger that CCS could take the wind out of the sails of renewables and energy efficiency. But many of the organisations refrain from formulating a stance of total rejection, recognising instead the potential bridging function of CCS but linking implementation to concrete conditions (e.g. no storage of CO_2 in the oceans, strict safety measures in storage, transparent independent monitoring and clarification of liability questions).

In the implementation of CCS, integrating the different social groups as early and as broadly as possible will be of decisive importance. Here a distinction must be made between potentially affected actors and the general public. A neutral and objective information strategy, conducted if possible (at least in part) by independent actors, will be here of decisive importance. Experience from the ongoing research and demonstration CCS projects can be used, especially with an eye to the question of how the complexities can be communicated to the public.

6 Conclusions and Outlook

Restricting the rise in global temperatures to a tolerable level demands swift action. A clear reversal of the trend is needed, which involves first to stop greenhouse gas emissions from increasing still further, and then to bring about a clear reduction in annual emissions. The energy sector assumes special significance here because its burning of fossil fuels results in the release of the greenhouse gas CO_2.

In the form of CO_2 capture and storage (CCS) a line of technology is under development that – if used to supplement a further expansion of renewable energies and increased exploitation of energy saving potential – could make a significant contribution to reducing energy-related greenhouse gas emissions. This has to be seen in context with global economic growth that is generally associated with increased use of fossil fuels. On the other hand, even if the global storage potential is, according to current knowledge, certainly considerable, there is a fundamental limit to permanent storage capacity. Hence a permanent solution to the climate problem cannot be achieved through CO_2 storage, but the technology line can fulfil an important bridging function.

CCS technology is not fundamentally new. The chemicals industry already has experience with CO_2 capture, and transport and storage of CO_2 has been practised for many years in a number of contexts and specifically in the oil and gas industry. But all the same, many questions remain to be answered before large-scale CCS technology can be implemented. Both technical and logistical aspects will have to be taken into consideration, the long-term behaviour of CO_2 in the various storage structures will need to be investigated, but most of all the corresponding institutional framework will have to be created. The latter encompasses first of all the general integration of CCS into national and international legal frameworks, clarification and transparent regulation of questions of liability (that are of considerable significance for public acceptance), the regulation of monitoring and reporting issues according to international guidelines (existing or yet to be evolved), such as the IPCC Greenhouse Gas Inventory Guidelines, and not least the creation of economic incentives for the implementation of CCS by integrating it in the Kyoto instruments or comparable mechanisms.

References and Bibliography

CEC. 2007. Accompanying Document to the Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions: Limiting Global Climate Change to 2 Degrees Celsius: The Way Ahead for 2020 and Beyond: Impact Assessment, commission staff working document. Brussels, 10 January 2007.

ECOFYS. 2004. C. Hendriks, W. Graus and F. van Bergen, Global Carbon Dioxide Storage Potential and Costs. Utrecht: ECOFYS, by order of the Rijksinstituut voor Volksgezondheit en Milieu, EEP-02001. (http://www.ecofys.com/com/publications/documents/GlobalCarbonDioxideStorage.pdf).

Edenhofer et al. 2004. O. Edenhofer, H. Held and N. Bauer, "A Regulatory Framework for Carbon Capturing and Sequestration within the Post-Kyoto Process". In Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies, ed. E. S. Rubin, D. W. Keith and C. F. Gilboy, vol. 1: Peer-reviewed Papers and Plenary Presentations. Cheltenham, UK: IEA Greenhouse Gas Programme.

European Council. 2005. Presidency Conclusions, document 7619/05. Brussels

European Council. 2007. Schlussfolgerungen der Tagung des Europäischen Rates vom 8. und 9. März 2007, document 7224/07. Brussels.

Ewers, Renzenbrink. 2005. J. Ewers, W. Renzenbrink, Bestandsaufnahme und Einordnung der verschiedenen Technologien zur CO_2-Minderung. VGB PowerTech 4/2005

Fischedick et al. 2006. M. Fischedick, W. Günster, H. Fahlenkamp, H-J. Meier, F. Neumann, G. Oeljeklaus, H. Rode, A. Schimkat, J. Beigel, D. Schüwer. CO_2-Abtrennung im Kraftwerk: Ist eine Nachrüstung sinnvoll? VGB PowerTech 4/2006: 1–10.

GESTCO. 2004. N. Christensen and S. Holloway, Geological Storage of CO_2 from Combustion of Fossil Fuel: The GESTCO project, Summary Report to the European Commission, Brussels.

Intergovernmental Panel on Climate Change (IPCC). 2005. Special Report Carbon Dioxide Capture and Storage.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: Working Group I, Summary for Policy Makers.

Intergovernmental Panel on Climate Change (IPCC). 2007. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, www.ipcc-nggip.iges.or.jp.

International Energy Agency (IEA). 2004. Report – Energy Technology Analysis: Prospects for CO_2 Capture and Storage. Paris.

International Energy Agency (IEA). 2006. World Energy Outlook 2006. Paris.

International Energy Agency (IEA). 2006. Good News for CO_2 Storage under the Seabed, IEA Greenhouse Issues, December 2006.

International Energy Agency (IEA). 2007. Carbon Dioxide Capture and Storage in the Clean Development Mechanism, Revolving CDM Methodology Issues, IEA Greenhouse Gas Research & Demonstration Programme, report scheduled for publication in spring 2007.

May, F.; Müller, Chr.; Bernstone, Chr. (2005): How much CO_2 can be stored in Deep Saline Aquifers in Germany? In: VGB PowerTech 6/2005.

May, F.; Müller, Chr.; Bernstone, Chr. (2005): How much CO_2 can be stored in Deep Saline Aquifers in Germany? VGB PowerTech 6/2005.

Meinshausen, Malte. 2006. What Does a 2°C Target Mean for Greenhouse Gas Concentrations? A Brief Analysis Based on Multi-gas Emission Pathways and Several Climate Sensitivity Uncertainty Estimates. In Avoiding Dangerous Climate Change, ed. H. J. Schellnhuber, W. Cramer, N. Nakicenovic, T. Wigley and G. Yohe, 265–279. Cambridge and New York: Cambridge University Press.

Öko-Institut. 2007. CO_2-Abscheidung und -Lagerung bei Kraftwerken, background paper for TAB workshop, Berlin, January 2007.

Schlattmann, Christian. 2006. Anforderungen an den Aufbau einer CO_2-Infrastruktur in Deutschland, M.Sc. dissertation, Fern-Uni Hagen, Fraunhofer UMSICHT.

Umweltbundesamt (UBA). 2006. Technische Abscheidung und Speicherung von CO_2 – nur eine Übergangslösung: Mögliche Auswirkungen, Potenziale und Anforderungen, Berlin.

Wuppertal Institut et al. 2006. Wuppertal Institut, Geologischer Dienst NRW. CO_2-Abtrennung und -Verwendung: Bewertung von Chancen und Risiken aus der Sicht des Landes Nordrhein-Westfalen, study commissioned by the North Rhine-Westphalia Ministry of Economics. Wuppertal.

Wuppertal Institut et al. 2007. RECCS – Strukturell-ökonomischer Vergleich regenerativer Energietechnologien (RE) mit Carbon Capture and Storage (CCS), commissioned by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU). Berlin.

Links

Intergovernmental Panel on Climate Change (IPCC): www.ipcc.ch

International Energy Agency (IEA) database on world-wide CCS projects: www.co2captureandstorage.info/

European research network on CO_2 sequestration: www.co2net.com/home/index.asp

Information on the first German CO_2 storage project in Ketzin: www.co2sink.org

Statement of the German Environment Agency (UBA) on CCS (in German): http://www.umweltbundesamt.de/uba-info-medien/mysql_medien.php?anfrage=Kennummer&Suchwort=3074

Publications on the subject of CCS from the Wuppertal Institute for Climate, Environment and Energy: www.wupperinst.org/ccs

GEOTECHNOLOGIEN (earth science research and development programme, funded by the Federal Ministry of Education and Research and the German Research Council, DFG): www.geotechnologien.de/forschung/forsch2.11.html

CO_2 reduction technologies research concept initiated by the Federal Ministry of Industry and Employment: www.cooretec.de

EU CCS technology platform: www.zero-emisssionsplattform.eu/website

Carbon Sequestration Leadership Forum (CSLF), an international climate protection initiative: www.cslforum.org

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