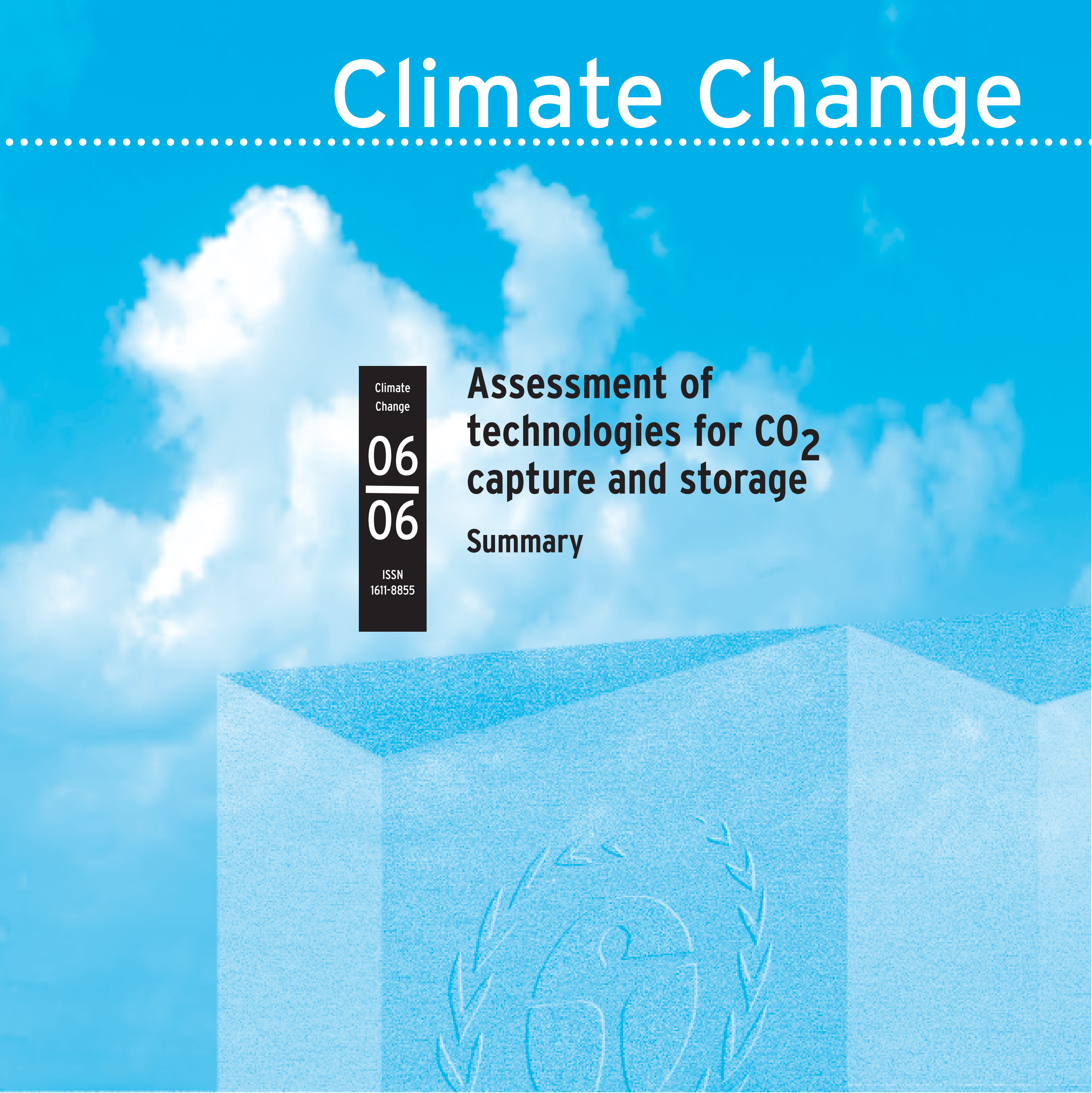

Climate Change

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Assessment of technologies for CO_2 capture and storage

Summary

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Assessment of technologies for CO_2 capture and storage

Summary

by

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in co-operation with

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

On behalf of the Federal Environment Agency

Note:
The term CO_2 storage used within this summary is oriented on the internationally common use of the term. The terms CO_2 sequestration or CO_2 disposal could also have been used as synonyms in this report.

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BGR

Summary

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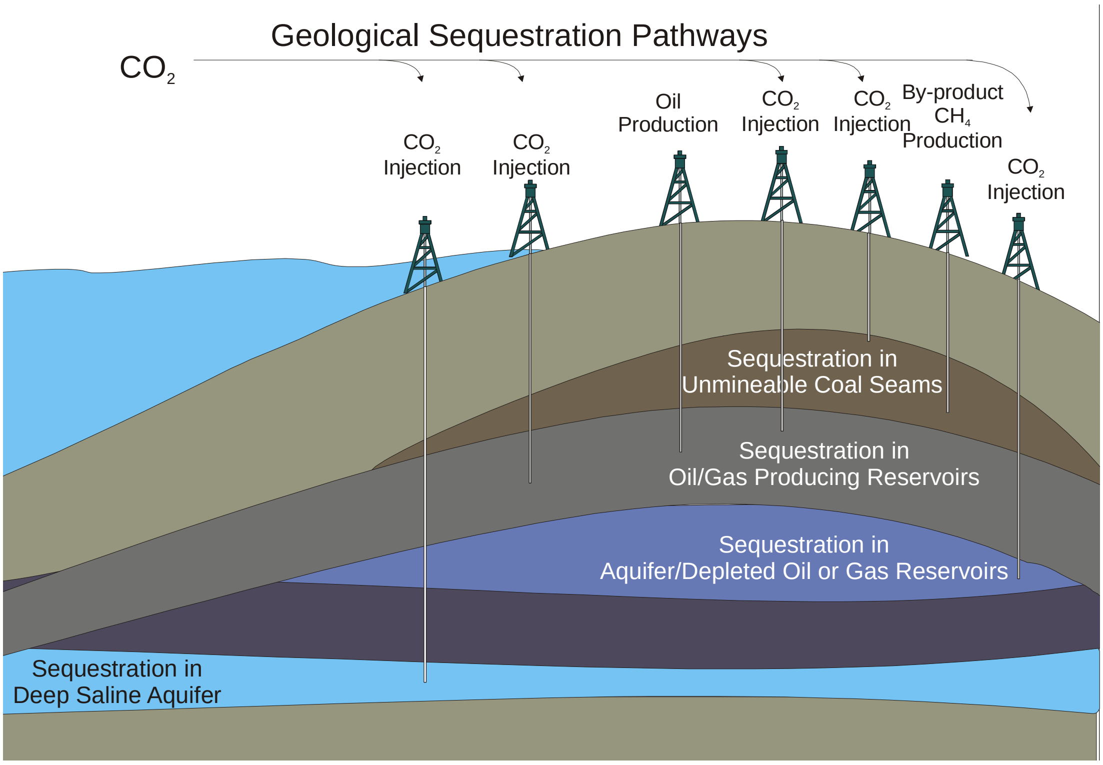

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16. Abstract

The aim of the study was to summarize the current status for carbon capture, transport and storage for CO_2 emissions from power stations. Special attention was given to the implications from the introduction of carbon capture and storage in power stations on the efficiency, emissions and costs for electricity generation. To start with, a detailed analysis was made of the national, European and international activities in this field. The analysis focused on the identification of main actors and the different cooperations of actors. To do this, the available literature was studied and analysed using a bibliometric approach which also took presentations at national and international conferences into account.

In the second step, a technical analysis was conducted for the three main routes of carbon capture (pre-combustion capture, post-combustion capture, oxy-fuel combustion) with special emphasis on the impacts on the environment. Truck, ship and pipeline transport were analysed as means of transporting the CO_2 from the power station to the storage site. In addition, the different storage possibilities for a secure, long-term storage of the captured CO_2 were studied in the report. Particular emphasis was placed on storage in gas fields and saline aquifers which are the most promising options in Germany.

The report thus provides an up-to-date review of the status of carbon capture and storage in the world. It therefore supports the decision-making process when introducing this new technology, taking into account the environmental effects.

17. Keywords
Carbon capture, carbon storage, power generation, pre-combustion, post-combustion, oxy-fuel, oil and gas reservoirs, gas clean-up

Contents

1 Introduction

This summary of the results of the research project "Assessment of technologies for carbon capture and storage" aims to give the reader a simple and lucid introduction to this topic. For this reason, the summary is compiled in the form of a theory paper. This aims to provide a quicker grasp of the subject. Those interested in more details or requiring more background information are recommended to read the final report. The individual issues to be addressed are listed as theses which are then commented upon in brief texts. These comments can only serve as an introduction to the subject because the issue of CO_2 capture and storage is a highly complex one. For this reason, the abbreviated and simplistic statements may lead to a distortion of the facts if the underlying frame conditions are not given in detail.

Average statements are usually vulnerable since it is always possible to find examples in which individual features of a technology may perform better or worse than the average statement. The data on capture, transport and storage are furthermore strongly characterized by project-specific frame conditions which influence the economic, ecological and social impacts. Alongside the quantitative statements, particular importance is given to qualitative statements and the development trend.

CO_2 capture and storage enhances low-emission electricity generation by a new technology option. A decision about which technology option is the best to realize a secure, environmentally-friendly, cost-effective, and sustainable energy supply is not easily possible since the individual technologies perform differently in the individual assessment areas. Here, a multidimensional assessment problem has to be solved in which the weighting factors among the individual target criteria are unknown. It can therefore be assumed that several technology options will be significant within the scope of sustainable energy supply in the future.

2 Background

A-1 Continuous increase in CO_2 concentration in the atmosphere e. g. (Hawaii).

A-2 Increase in CO_2 emissions results in climate change.

A-3 The limited availability of fossil energy resources will probably not affect the extent of their use and thus emissions in the short to medium term.

A-4 The combustion of fossil energy sources has a large share in the increase in CO_2 concentration.

A-5 Fossil fuels will still be of great significance for the energy supply in the next 30 to 50 years despite the development of renewable energy sources.

A-6 In the near future, approx. 40 GW of power generation capacity have to be constructed in Germany alone. The service life of a conventional power station is typically more than 40 years.

A-1

Figure 1 shows the continuous increase in CO_2 concentration in the atmosphere since January 1958. This is the longest continuous record of atmospheric CO_2 concentration available in the world measured at the Mauna Loa Observatory on Hawaii. Apart from seasonal fluctuations, a continuous increase can be observed.

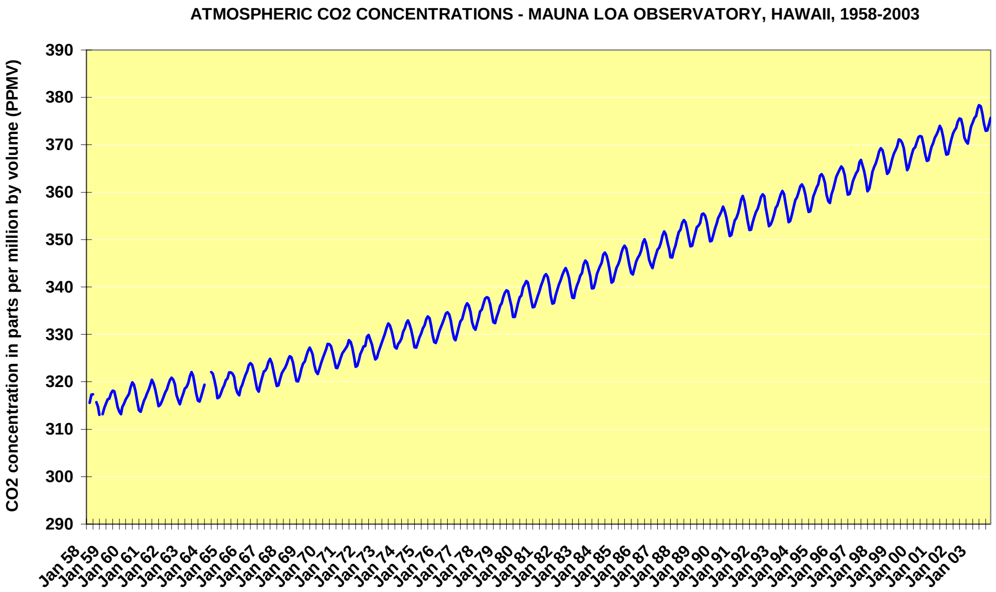

Figure 1: Increase in the concentration of CO_2 in the atmosphere monitored by the Mauna Loa observatory, Hawaii
(data: http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm)

A-2

Based on the individual Assessment Reports of the International Panel on Climate Change (IPCC), there is a general consensus today that the greenhouse gas emissions from burning fossil fuels have an impact on climate change. The CO_2 concentration in the atmosphere is in direct correlation with the increase in average temperatures. The resulting imbalance triggered by the increase in concentration results in a change in climate, the intensity of which, however, cannot be predicted exactly at present.

A-3

The main projections for the global markets for fossil fuels, especially the World Energy Outlook of the IEA (2004), assume a continued balanced relationship of supply and demand for all fossil energy sources at a moderate price development for the period up to 2030. In view of these projections, a continued utilization of fossil energy sources should be expected as long as the economic frame conditions are not altered by other factors of influence such as significant emission restrictions or allowance prices.

A-4

As far as climatic impact is concerned, carbon dioxide emissions make up a share of more than 80 % of anthropogenic greenhouse gas emissions. Of the CO_2 emission sources, installations producing electricity and heat play the most important role worldwide. In 2001, this sector was responsible for almost 40 % of CO_2 emissions. The second largest share of 24 % is from the transport sector. Since the installations for electricity and heat generation are frequently larger stationary emission sources, whereas in the transport sector, small and usually mobile emission sources are the rule, it seems wise to make the first move in applying CO_2 capture and storage by focusing on electricity and heat generation.

A-5

Although there has been a massive expansion in the use of renewable energies in the last few years, their share in primary energy consumption (3.6 % in Germany in 2004) and electricity generation (9.3 % in 2004) is still far from being able to replace fossil energy sources as the basis for the energy supply. At present, the majority of energy scenarios assume that fossil energy sources will still hold a share of at least 50 % in the energy supply in 2050. At the current reserves of approx. 50 years for oil, 70 years for gas and 300 years for coal, avoiding CO_2 emissions is therefore assigned a higher significance in the short term than reducing resource consumption.

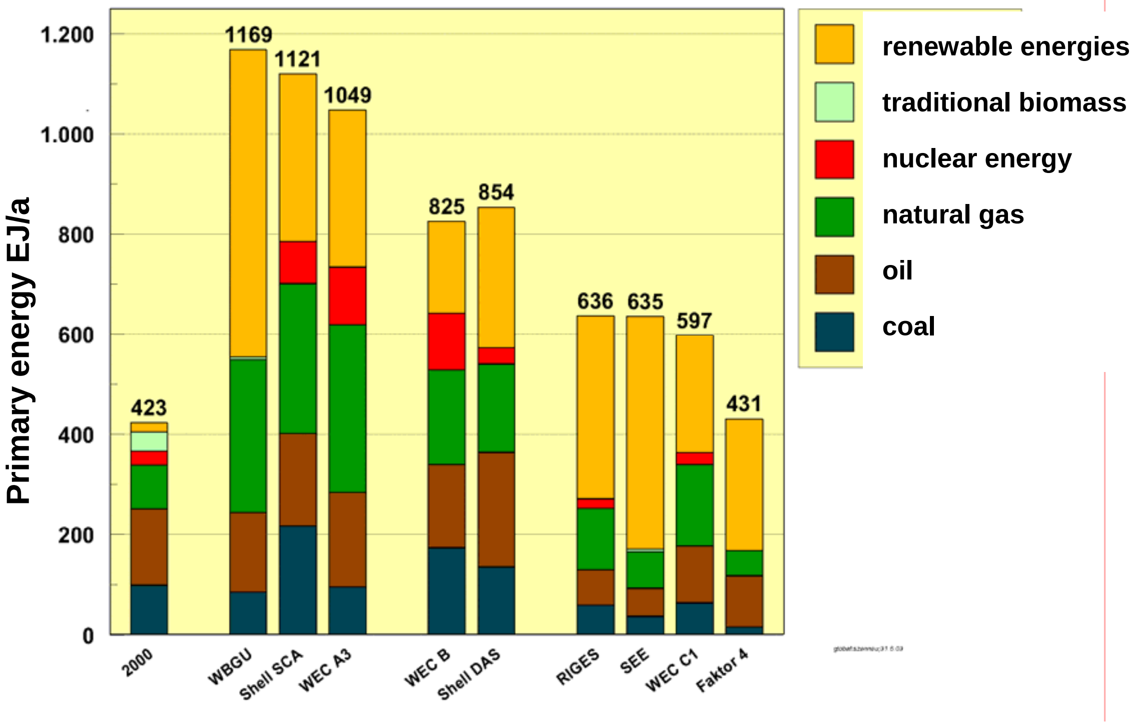

Figure 2: Current scenarios of global primary energy consumption for the year 2050 with a population increase up to 9 to 10 billion
Sources: WBGU 2003; WEC 1998; Shell 2001; Johannson 1993; Lovins/Hennicke 1999; Nitsch 2003 cited in: Ökologisch optimierter Ausbau der Nutzung erneuerbarer Energien in Deutschland, BMU 2004.

A-6
Determined by the age structure of the existing power generation system in Germany and the decision to phase-out nuclear energy, power stations with a capacity of around 40 GW will have to be replaced in the next 15 to 20 years. Since these new power stations will then probably operate for a further approx. 40 years, the investment decisions made in the next few years will strongly influence the structure of electricity generation in Germany. In order to achieve a noticeable medium-term reduction in energy-induced emissions without causing stranded investments, it is therefore necessary to invest in low-emission electricity generation technologies now. As well as using renewable energies, increasing energy efficiency and expanding CHP, fossil-fired power stations with CO_2 capture and storage could also make a contribution here.

3 Stakeholders

B-1 Oil and gas companies play a leading role due to their geotechnical expertise and special incentives.

B-2 Electricity producers are examining the topic due to the obligation to reduce emissions under the European emissions trading scheme.

B-3 The coal industry gets a boost due to low-emission coal-fired power stations.

B-4 The US recognizes the potential of low-emission power stations to become a driver of technology exports to Europe, China and India and has therefore launched large public support programmes.

B-5 Sponsored by the European Union under the 5th, 6th and 7th Framework Programmes, the European power industry is beginning to take up the challenges (EU Technology Platform "Zero Emission Fossil Fuel Power Plants").

B-6 Germany, the UK and Norway are drivers within the EU (ERA Net FENCO; CSLF, COORETEC…).

B-1
The large international oil and gas companies have many years of extensive experience in handling CO_2 in connection with the extraction of oil and gas. For instance, several companies have been injecting CO_2 into oil and gas fields for a long time to improve their yields (EOR/EGR). In addition, the natural gas extracted from many reservoirs contains shares of up to 25 % CO_2. In order to render the gas marketable, the CO_2 has been separated from the natural gas and subsequently emitted to the atmosphere for many years.
Furthermore, the technologies used to explore oil and gas reservoirs are also suited to exploring possible CO_2 repositories. The activities of oil and gas companies can probably be explained by the fact that they perceive the continued use of fossil energy to be threatened less by the scarcity of the resources and more by their impacts on the global climate.

B-2
There have been two radical changes for power suppliers in Germany in the past few years. These are, on the one hand, the decision to phase out nuclear energy and, on the other, the start of emissions trading on 1.1.2005. The latter has led to greenhouse gas emissions being assigned an economic value. Due to emissions trading, it is now worth thinking about whether it is economically more sensible to avoid emissions or to purchase the necessary emission allowances. Correspondingly, there has been a recent massive surge in the efforts to increase efficiency and reduce CO_2 emissions so that new technologies are now almost ready for the market.

B-3

The option of low-emission, coal-fired power stations represents a (new) opportunity for the coal industry to continue their activities even under strict climate policy frame conditions or indeed even be able to expand them. If the possibility of CO_2 capture and storage is not considered, there is the real danger that the coal industry will no longer be successful on the electricity market in the medium term. For this reason, CO_2 capture and storage is seen as a definite benefit by the players in this sector and is being correspondingly pursued with relatively strong commitment.

B-4

In the USA, a multitude of state funded projects are being conducted which contribute to improving the efficiency of power stations which capture CO_2 as a whole or increasing the efficiency of sub-processes. Also supported are projects which help to test the feasibility of CO_2 storage or are designed to develop criteria for storage safety and to determine the costs and potentials for storage projects. The use of significant funds particularly from the public sector is justified in many cases with the argument of promoting future technology exports to countries which have ratified the international agreements on climate protection.

B-5

In the European research landscape, the research and development activities of technology producers are increasing. The EU is promoting these activities especially within the scope of the Sixth Framework Programme and is trying to coordinate them via the EU technology platform "Zero-Emission Fossil Fuel Power Plants". This is a reaction to the technological challenge posed by the US. This is clearly illustrated by the example of hydrogen-powered gas turbine development for which corresponding efforts are being made on both sides of the Atlantic. Another example is the implementation of a demonstration power station with CO_2 capture and hydrogen production in the EU under the heading HYPOGEN and in the US under the heading FutureGen.

B-6

In Europe, a large part of the research activities take place within the programmes of the European Union. Nevertheless, there are still certain EU countries emerging as pioneers in this field due to intensified autonomous national programmes and projects. At present, stronger activities can be observed in Norway, the United Kingdom and also more recently in Germany. One example for this is the FENCO initiative with the UK and Germany as the main partners, which aims to coordinate the national activities on developing low-emission CO_2 power stations within the European research landscape. In Germany, development activities are pooled under the COORETEC programme of the Federal Ministry of Economics and Labour.

4 Basic sub-processes

C-1 Separation: the conversion processes of fossil fuels are modified such that CO_2 can be separated from the process

C-2 Transport: CO_2 is compressed and dried and then transported to a storage location by pipeline or ships

C-3 Storage: CO_2 is injected into geological formations in which it can be kept out of the atmosphere for very long periods

C-1

CO_2 separation means modifying the conversion processes of fossil fuels so that CO_2 can be separated from the process in a pure or highly enriched form. The flue gases resulting today from the combustion of fossil energy sources usually contain 5 – 15 vol.-percent CO_2. CO_2 concentrations of more than 90 % have to be achieved for efficient storage. The processes currently in use and being developed intervene at different points of the conversion process and are divided according to the point of intervention into post-combustion capture, pre-combustion capture and oxy-combustion, see **Figure 3**.

C-2

As it cannot be assumed that suitable storage possibilities exist at all or even at the majority of locations at which CO_2 separation will take place, large volumes of CO_2 (in the order of several million tons per year from a large power station) will have to be transported. Either pipelines or ships are eligible for the economic transportation of such volumes. For efficient transport, the CO_2 has to be converted either into the supercritical (or "dense" phase) or the fluid phase.

C-3

To store CO_2, it will be placed in a compartment of the geosphere or hydrosphere in which it can be kept out of the atmosphere for a long period of time. Geological formations are currently being considered in Europe, whereas the USA and Japan are also investigating the water columns of the oceans as a storage medium for CO_2. When storing CO_2 in geological formations, it is placed in underground porous rock formations (at depths of approx. 1000 m to 2500 m), which are sealed from above by the presence of impermeable layers of rock.

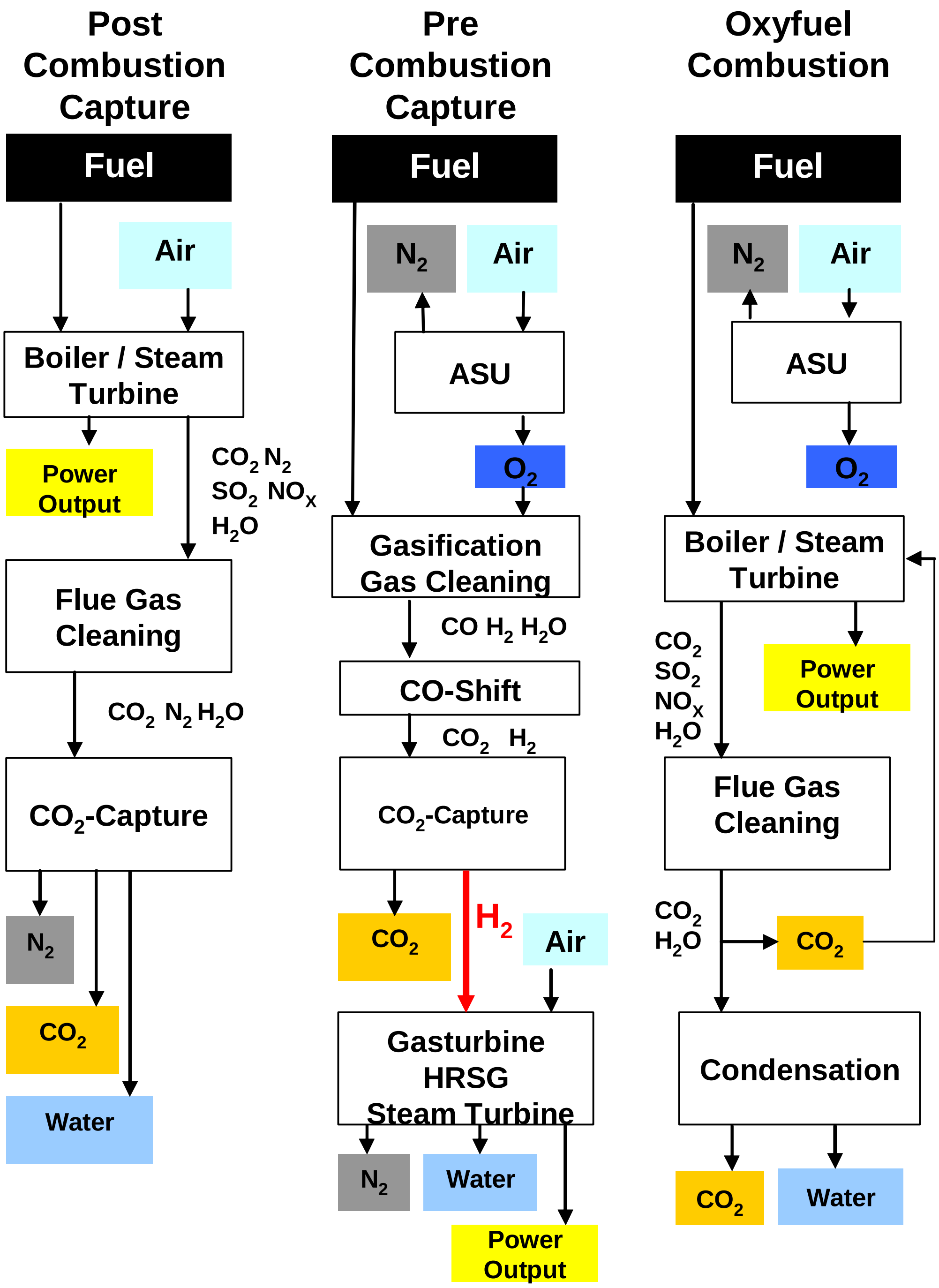

Figure 3: Schematic illustration of the three main processes of CO_2 capture

4.1 Separation

D-1 Post-combustion: separating the CO_2 using a chemical scrubber which takes place downstream after a more or less unchanged conventional combustion process, comparable to the process of wet desulphurization of flue gases.

D-2 Pre-combustion: separating the CO_2 from a fuel gas produced by the gasification of solid fuels or reforming of gases using physical scrubbers prior to the main energy conversion process.

D-3 Oxy-combustion: combustion of carbon energy sources using (almost) pure oxygen which results in a flue gas consisting of CO_2 and steam from which storable CO_2 can be recovered by simple drying or condensation.

D-4 The high additional energy demand of CO_2 separation results in an efficiency loss of 8-18 % points in the power station and thus in a clear increase in the consumption of resources.

D-5 Capture rates lie between 85 % and 95 % (post/pre) or around 98 % (oxy); i. e. a zero-emission power station does not exist, only a low-emission one.

D-6 Additional costs amount to approx. 100 % of the current electricity generation costs of a fossil power station, which are currently between 1.5 and 2.5 ct./kWh

D-7 Costs are approx. 20-50 Euro/ton of captured CO_2 or 24 -75 Euro/ton of avoided CO_2 emissions.

D-8 A limited number of options with lower costs are suitable for demonstration projects. Possible options would be the storage of CO_2 from installations in which it has to be separated in any case such as, e.g. H_2 generation, ammonia production, refineries or when using gas deposits with a high proportion of CO_2.

D-1

Post-combustion: capturing the CO_2 by scrubbing downstream from a conventional combustion process. The flue gas would undergo an additional process similar to wet desulphurization after the usual flue gas cleaning to remove dust, nitrogen oxides and sulphur. The flue gases usually formed can only be separated cost-effectively using chemical scrubbers because of the low partial pressure. Extensive application experience with chemical scrubbing is available from using amine scrubbers in the process industry (e.g. for ammonia synthesis). The flue gas is brought into contact with the amine-based scrubbing solution in absorber columns to remove the CO_2. The scrubbing solution is then recycled and regenerated in a desorber (stripper tower) by applying energy (steam). If the system sizes commonly used in the process industry were applied to CO_2 separation in power stations, 6 absorbers of 35 m height and with a diameter of 3 m and the relevant desorbers would be necessary for a coal-fired power station with approx. 400 MW net electrical output (corresponding to approx. 1000 MW thermal output).

If this type of amine scrubbing were used for CO_2 capture from flue gases, problems could be expected with the oxygen sensitivity of amines which result in amine degradation and corrosion problems. As a result, a considerable consumption of amines could occur and perhaps problems with disposing of the residues. In addition, due to the low steam pressure, it has to be reckoned that some amine will escape with the flue gas from the separation process.

D-2

Pre-Combustion: in pre-combustion capture, the CO_2 is separated from a fuel gas prior to the main energy conversion. The main energy conversion to produce secondary energy carriers then takes place using a carbon-free energy source. Solid fuels such as hard coal, lignite or biomass are converted into a synthesis gas in a gasifier and natural gas by reforming in a steam reformer. The synthesis gas is reacted with additional steam in the water-gas shift reaction to yield a mix of mainly CO_2 and hydrogen. CO_2 is then separated from this gas using a physical scrub which is the most cost-effective for the higher partial pressures of the CO_2 reached in the synthesis gas. Particularly suitable solvents include methanol, propylene carbonate or normal methyl-pyrrolidone. On account of the smaller gas flows prior to combustion, smaller scrubber sizes are possible than is the case in downstream separation processes. Another advantage is the lower energy consumption involved due to the regeneration of the solvent via pressure release (release of the dissolved CO_2) and recompression and cooling (recycling of the solvent). In addition, pollutant emissions of other substances such as SO_2 and heavy metals can also be eliminated to a large extent at the same time which drastically reduces these emissions from coal and lignite use compared to conventional combustion plants.

Using chemistry and process technologies, pre-combustion capture creates an additional technology focus in power stations, which is typically the field for mechanical and electrical engineering and thus to some extent demands other qualifications from the operating personnel. The technology is not suited to retrofitting existing power stations because of the fundamentally different process involved.

D-3

Oxy-combustion: in combustion processes using oxygen instead of air as the oxidant, the main separation process is shifted to the side of the oxidizing agent. Atmospheric oxygen is separated from nitrogen, the principal component during this separation. During the combustion of fossil fuels or biomass with oxygen, a flue gas is produced which basically consists of CO_2 and steam depending on the hydrogen content of the energy source. The steam can be subsequently separated by simple drying or condensation without excessive energy use. Oxy-combustion is still at the development stage and has not yet been tried and tested, and controlling the combustion presents a particular challenge. The high energy demand for producing the oxygen is one disadvantage of this technology, although this might be able to be reduced by applying membrane-based processes for oxygen production. Approx. 2.7 kg of oxygen are needed for the combustion of 1 kg of hard coal (3.6 kg oxygen for 1 kg natural gas). At present, the most energy-efficient way of supplying oxygen by breaking air down into its respective compo-

nents is based on cryogenics. An electricity demand of 0.21 to 0.29 kWh_{el}/kg oxygen (at 99.5 % volume share) is required for oxygen production in these processes.
Oxy-combustion does not offer any possibility of supplying hydrogen in an integrated conversion system. Nor is any possibility expected in the medium term of applying the combined cycle for solid fuels with oxy-combustion since there are no prospective solutions for efficient hot gas cleaning.

D-4
All the discussed methods of CO_2 separation cause an additional high energy demand which results from the actual separation, the regeneration of solvents, the poorer efficiency of the core process and the energy required for the compression and drying of the CO_2 into a transportable and storable state. At present, efficiency losses in the order of 8-18 % points are calculated, although the values cited in the literature vary widely both within a technology group and among technology groups. Based on today's technology data, resource consumption would increase by a factor of approx. 1.2 (natural gas power station), up to about 1.6 (hard coal power station) and approx. 1.8 (lignite power station). If future technologies with higher efficiencies are compared, the factors will probably be around 1.1 (gas), 1.2 (coal) and 1.4 (lignite).

D-5
The achievable separation rates are below 100 % in all processes. Basically, there is no zero-emission power station, there can only be low-emission power stations. In installations with post-combustion or pre-combustion capture, capture rates are typically between 85 % and 95 % of the emitted CO_2. In pre-combustion, the achievable rate is mainly determined by the degree of conversion of the carbon monoxide in the synthesis gas into carbon dioxide in the so-called shift reaction. There is a noticeable rise in the operating expenses for further conversion. Capture rates of approx. 98% can be achieved using oxy-combustion methods.

D-6
The additional costs for the capture of CO_2 from electricity generation processes are in the order of 1.5 to 2.5 ct/kWh and thus around 100% of the current electricity generation costs. The additional costs are incurred mainly due to the higher plant costs resulting from the additional components necessary for separation and compression, the increased demand for fuels resulting from decreased efficiency and the additional operating materials for the CO_2 capture. Furthermore, the reduced overall efficiency results in larger installations being necessary to achieve the same net output capacity of the power plant.

D-7
The costs for CO_2 capture amount to 20 to 50 Euro/ton of separated CO_2. The wide margin results from the very different values cited in the literature not only for individual technology groups but even within such groups. Based on avoided CO_2 emissions, the cost estimates range from 24 to 75 Euro/ton CO_2. The costs are higher since more

CO_2 emissions occur in power stations with CO_2 capture due to their reduced overall efficiency than at a reference power station with a comparable electrical net output without CO_2 capture. For this reason, the amount of captured CO_2 is higher than the amount of the avoided emissions which in turn explains the different cost figures for the two reference values.

D-8

Alongside the possibility of capturing CO_2 from power stations, there are a limited number of options for CO_2 capture in industrial processes where CO_2 can be separated cost-effectively. These primarily concern industrial installations in which CO_2 has to be separated as an integral part of the process involved, such as e.g. installations for the production of H_2, for ammonia synthesis and refineries or plants with flue gases with very high concentrations of CO_2 such as blast furnaces or plants for producing cement and lime. The cost-efficient options for CO_2 capture which already exist here could be very suitable for demonstration purposes of the total process chain. However, the different composition of the gases from which the CO_2 has to be separated has to be taken into account. There are significant differences in the proportions of dust and oxygen involved.

4.2 Transport

E-1 High costs for compressing or liquefying the CO_2 (energy demand approx. 0.12 kWh/ton CO_2 110 bar)

E-2 Only practical to transport the amount involved (> 1 million tons /a and power station) via pipeline or ship

E-3 The direct dangers from CO_2 are relatively low (non-toxic)

E-4 Pipeline accidents are rare and extensive experience is available with O_2, N_2, CH_4 and H_2 pipelines

E-5 At present no CO_2 transportation infrastructure exists in Europe. There is a high financial risk of investing in this infrastructure, comparable with the problems of developing a hydrogen infrastructure

E-1
The transportation of the large volumes of CO_2 collected by CO_2 capture is only economic in a supercritical (also: dense) or liquid state, since in a gaseous form, the volumes to be transported would be too large. As a result a considerable amount of energy is required to transfer the CO_2 into the dense or liquid state, which is in turn expressed in high costs for this process step. The energy demand for compressing CO_2 from atmospheric pressure to 110 bar amounts to approx. 0.12 kWh/ton CO_2.

E-2
The amount of CO_2 produced as a result of separation processes in power stations in the order of 1 to 10 million tons CO_2 per year and power station can only be feasibly transported by pipeline or ship. Its transport by ship will probably take place in a liquid state since pressurized storage tanks are not available in the size required for this. A larger number of small tanks on board a ship would present an unfavourable ratio of storage volume to the surface volume required which would result in a smaller freight volume. In pipelines, CO_2 is transported in a dense state at pressures of usually more than 100 bar in order to avoid a phase transition into the gaseous phase. The amounts to be transported would greatly exceed the capacity of the existing transportation infrastructures by rail or road vehicles.

E-3
The dangers associated with transporting CO_2 are comparatively low since CO_2 is neither flammable nor explosive nor poisonous. Compared with other gases such as natural gas, blast furnace gas or hydrogen, which are also transported by pipeline, it poses a lower basic threat. Due to the tendency of gaseous CO_2 to accumulate in poorly ventilated sinks because of its higher density compared to air, the only danger may be due to dangerous CO_2 concentrations if leaks did occur. However, this danger is estimated as comparatively low and can be further restricted by the careful routing and monitoring of pipelines.

E-4

Accidents connected with the operation of pipelines are rare and extensive experience has been accumulated in Europe with the operation of pipelines to transport natural gas but also manufactured gases such as oxygen, nitrogen or hydrogen. In addition, there are pipeline networks in the US to transport CO_2 from natural deposits and industrial installations to supply the oil producing regions with CO_2 for tertiary oil production. Based on the operating results of these pipelines, it can be concluded that pipeline transport can be managed safely.

E-5

At present there is no infrastructure for transporting CO_2 in Europe. Similar to investments in comparable transport infrastructures, the construction of individual pipelines or networks of pipes entails a considerable capital outlay. The long amortisation periods common to infrastructures bring about a long capital lockup and thus a high investment risk.

4.3 Storage

F-1 CO_2 storage in geological formations (aquifers, depleted oil and gas fields) is favoured in Europe.

F-2 Ocean storage is not being pursued in Europe.

F-3 CO_2 storage in combination with measures to increase the extraction of oil and gas (EOR/EGR).

F-4 Sufficient storage capacities for approx. 50 to 100 years are available in saline aquifers, but sources and sinks are often not optimally situated in relation to each other.

F-5 CO_2 storage in aquifers is being demonstrated on an industrial scale (Sleipner; In Salah).

F-6 There are uncertainties about the amount of possible leaks from repositories and the leakage rate which can be tolerated.

F-7 Regarding carefully selected storage formations, the main risks for leaks are the boreholes and their seals.

F-8 The questions of who should monitor the intactness of the storage facility, with which methods this takes place and how long the monitoring would have to be conducted are of high importance.

F-9 With regard to storage, there are great uncertainties about authorization issues with regard to concrete implementation.

F-1

Aquifers or depleted oil or gas reservoirs are being considered for CO_2 storage in Europe because the technical feasibility of these geological formations has been more or less clarified on the one hand and because a high degree of storage security and low environmental impact are expected on the other.

Aquifers are porous underground rock formations which have the property of being able to transport and store liquids and gases due to their porosity and permeability. Deep saline aquifers are used for storing CO_2 (depth lower than 800 m, so that the CO_2 remains in the supercritical phase), whose water content is not eligible for groundwater use. In addition, suitable aquifers must be sealed from above by the presence of impermeable rock layers. When storing CO_2 in a saline aquifer, first of all the formation water has to be driven out and the pressure in the aquifer increases. At the dispersion front, the CO_2 slowly dissolves in the formation water. In the long term, over several decades and centuries, the stored CO_2 will gradually be dissolved and over even longer periods mineralised by reactions with the rock matrix. The use of aquifers for CO_2 storage is currently competing with the use of hydrothermal geothermal energy from these aquifers.

The basic procedure of storing CO_2 in oil or gas reservoirs does not differ from aquifer storage since the repositories are also porous rock formations which are sealed from above. Based on the fact that oil or gas has been retained there for long periods, it can be assumed that the reservoirs have a high level of geological storage security. In principle, CO_2 can either be stored in depleted reservoirs or injected into still active ones in order to increase their output (EOR/EGR; see F-3). As far as storage in geological formations is concerned, those under the ocean floor could also be used. This kind of CO_2 storage does not usually come under the heading of ocean storage.

F-2

Direct ocean storage of CO_2 is understood to be the injection of CO_2 into water columns in the world's oceans in order to keep it out of the atmosphere for a limited period of at least several decades. At present, various methods of injecting CO_2 into the ocean are being investigated, mostly in Japan and the USA, which involve different depths and different procedures. Depending on the depth of injection, it is assumed that the CO_2 will dissolve in the seawater or that lakes of supercritical CO_2 will be formed on the seabed. Ocean storage has not yet been commercially tested. There are great reservations here both with regard to the duration of storage in the ocean and with regard to the environmental impacts, especially on marine flora and fauna.

Indirect ocean storage is understood to be the fertilisation of seawater in order to generate an increased growth in plankton in ocean regions in which lack of minerals (primarily iron) is the limiting factor for plankton growth. After the plankton dies, it is expected to sink down to the ocean floor taking the carbon absorbed with it and thus storing CO_2 in the biomass on the seabed. This process still has to be explored scientifically and the chances for success are uncertain.

Low to very low public acceptance must be reckoned with for both kinds of ocean storage in Europe.

F-3

In many cases where oil or gas production is slowing down, output can be increased by injecting CO_2 into the reservoir. The injection increases the reservoir's pressure and on top of this reduces the oil's viscosity which then flows better to the production wells. Up to now, these measures which are known as "enhanced oil recovery (EOR)" and "enhanced gas recovery (EGR)" are mainly used in sites in the southwest of the US. Here the injection of CO_2 is used only to increase yield levels and no attempt is made to store it. In fact, quite the opposite is true: as much as possible, the CO_2 is extracted with the hydrocarbons and recirculated since, as an additional resource, it represents a cost factor. The industrial selling price for CO_2, e.g. for use in the food industry, is typically between 50 and 100 Euro/ton CO_2.

In Weyburn (Canada), in contrast, the first field trial is taking place in which CO_2 is to be deliberately stored within the scope of EOR measures. The significance of storing CO_2 in connection with EOR and EGR is high since the CO_2 has its own economic value as an operating material, which is set against the costs for capture and transport and thus could improve the economic balance of CO_2 separation. However, there is a comparatively short time frame for many North Sea oil fields in which such measures could be begun before extraction has to be stopped for economic reasons.

F-4
The magnitude of the amount of CO_2 storable in geological formations in Germany has not been conclusively settled since, on the one hand, geological exploration is not yet sufficient in most cases in order to make statements about the usability of reservoirs and, on the other, the requirements made of the storage conditions have not been clarified. Nevertheless, it can be estimated that sufficient storage capacity is probably available in saline aquifers for 50 to 100 years. However, the position of sources and possible sinks relative to one another is likely to be suboptimal in many cases and will give rise to longer transit routes.

F-5
CO_2 storage in geological formations is already being practised on a commercial scale in demonstration projects at the "Sleipner" field in the North Sea and in gas extraction at "In Salah" in Algeria (each in the order of 1 million tons CO_2 per year). In both cases, the CO_2 has to be separated from the natural gas and is then forced back underground instead of releasing it to the atmosphere as is usually the case. In the "Sleipner" gas field it is injected into an aquifer underneath the gas bearing layer, whereas in "In Salah" it is being stored with a certain horizontal offset in the gas bearing aquifer. This is purely a storage measure with no associated increase of output. The demonstration projects aims to explore the feasibility of aquifer storage and the behaviour of CO_2 in aquifers.

F-6
The amount and spectrum of possible leakage rates from geological storage is not yet known. Basically, leaks from storage reservoirs can never be completely eliminated. If storage reservoirs are located underneath aquifers used for drinking water supplies, leaks could bring about an infiltration of CO_2 and thus a drop in the pH level. This could result in a change of the water chemistry. Repositories should always be selected on the basis that there are several layers above the storage reservoir acting as a barrier and that a back-up reservoir is available (principle of multiple barriers).

F-7
Assuming the relevant advantageous natural geological conditions are given, the main causes for leaks are likely to be the manmade breaks through the covering layers at the wells. Correspondingly, the careful geotechnical sealing of all boreholes reaching the storage reservoir is very important. The long-term intactness of geotechnical seals probably still represents a technological challenge. The problems of possible leaks at boreholes is less critical to the extent that these points of possible permeability are easy to monitor and should leaks occur these will be able to be re-sealed using technical measures.

F-8
A sustainable emission reduction for climate protection assumes that the intactness of the CO_2 storage is maintained over long periods of time. Thus, for an emissions trading system to function properly, it must be guaranteed that the stored CO_2 remains at the

storage site via regular monitoring and verification. Up to now, no solution is in sight as to who should bear the responsibility for the monitoring, how long it should be continued and who will pay for it. It must be borne in mind that the storage duration required is likely to be much longer than the classical life cycles of power stations or the lifespan of many companies.

F-9

The necessary legal preconditions for carrying out a CO_2 storage project are still very unclear in Germany. Since there have not been any precedents on German territory on a commercial scale, no conclusions can be drawn from them. Only in the "CO_2Sink" research project is a limited amount of CO_2 being stored and a legal process played through. In principle, however, it can be assumed that the mining law, the water laws and also laws on waste will have to be applied. To what extent new legal regulations will be necessary is still an open question, as is the question of which authority will be responsible for the official authorization and monitoring of CO_2 storage.

5 Society

G-1 Public knowledge of the technology is still very limited

G-2 Judgements about CO_2 capture and storage are usually dependent on the context in which the question is asked

G-3 The European emissions trading system does not offer sufficient long-term price security on its own for investments in CO_2 capture and storage. In the Netherlands, a fixed payment for power from zero emission sources is creating the necessary investment security.

G-1

There is still little general public knowledge about CO_2 capture and storage as an emission reduction measure. One reason for the limited familiarity is probably that the technological concepts are still very new and the demonstration projects realised so far in Europe/North Africa have been conducted in uninhabited regions (North Sea/Sahara). There has also been a very limited amount of social-sciences research activity on this technology field up to now. For example, there have only been scientific studies on the public acceptance of these technologies and the associated encroachments on nature in a few countries of the EU. Furthermore, the studies are very restricted in their coverage.

G-2

The judgements made in surveys about CO_2 storage technology were strongly dependent on the context of the question in which the usually unknown technology was introduced. However, it can be assumed that the judgements will be more critical when made by persons in the neighbourhood of potential storage locations for CO_2 and in the context of concrete projects. It should be noted that a planned field trial for CO_2 storage in the ocean off Hawaii has already been abandoned because of public protests.

G-3

Under the current techno-economic prerequisites and forecasts, the construction and operation of power stations with CO_2 capture is not profitable. Nor will the introduction of the European emissions trading system greatly improve profitability since the allocation of emission allowances, which is first restricted to three years and later to five, does not provide enough investment security for the construction of power stations. The CO_2 capture and storage technology will only be realised without additional support if the players involved in the electricity and emissions trading market have long-term high price expectations for CO_2 emissions.

In the Netherlands, a fixed payment for power from zero emission sources is creating the necessary longer term investment security and a first 50 MW commercial power station with CO_2 capture and storage is currently in the realisation phase.

6 Outlook

The separation and storage of CO_2 from power station processes represents one possibility to substantially reduce the CO_2 emissions from the electricity generation sector within the next 20 to 50 years. Since the power generation system in Germany and the EU will require massive modernization in this period anyway, power stations with almost zero CO_2 emissions could be built in the course of already planned replacement investments. Due to the specific emission factors of the individual fuels, coal-based power stations in particular should be decarbonised since there is an additional reduction of other pollutants here and efficiency gains could be achieved by making the combined cycle technology utilizable for solid fuels when generating electricity.

Power stations in which pre-combustion is used for CO_2 separation also offer the possibility of producing hydrogen cost-effectively. This would have a favourable impact on a possible hydrogen economy.

Moreover, it should be noted that capturing CO_2 in power stations would cost us the efficiency gains achieved over the last 50 years and would increase resource consumption by about a third. Power stations with CO_2 capture can thus not be designated "sustainable energy production." From a purely economic viewpoint, this technology currently compares favourably with other low-emission electricity generation technologies such as, e.g. photovoltaic, wind or biomass, in spite of the considerable additional costs when compared with conventional power stations. However, even with all its apparent present advantages, CO_2 capture and storage should not be seen as the solution to the climate problem. Rather, it represents only one conceivable bridging technology until renewable energy sources are sufficiently developed (with regard to amount and price) since the available storage capacity in Germany would probably only be sufficient for about 50 to 100 years.

In order to realize short-term emission reductions, energy efficiency measures in energy use should also be strongly supported alongside efforts in the field of energy transformation (renewable/fossil energy sources).