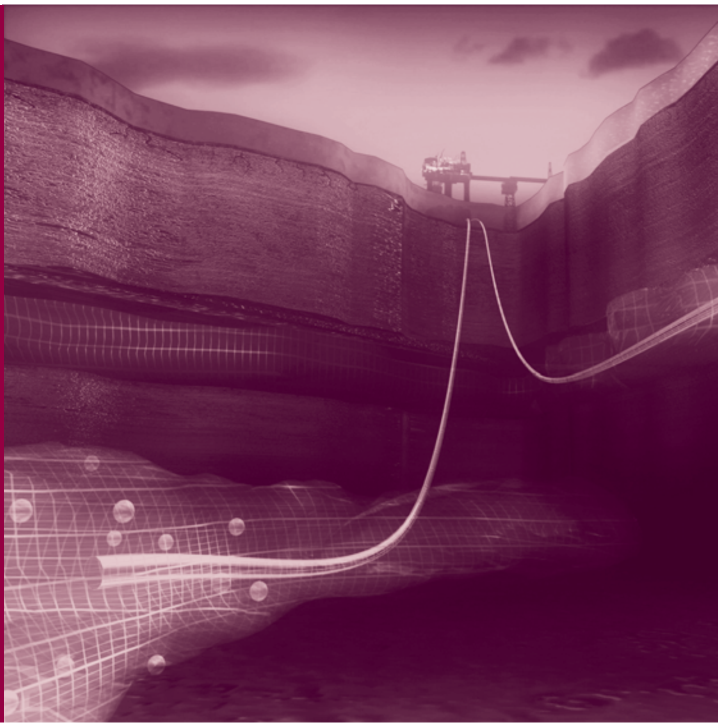
OFFICE OF TECHNOLOGY ASSESSMENT
AT THE GERMAN BUNDESTAG

Reinhard Grünwald

Greenhouse Gas – Bury it into Oblivion

Options and Risks of CO_2 Capture and Storage



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GREENHOUSE GAS

TECHNOLOGY ASSESSMENT STUDIES SERIES, NO 2

The Office of Technology Assessment at the German Bundestag is an independent scientific institution created with the objective of advising the German Bundestag and its Committees on matters relating to research and technology.

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TAB's task is to design and implement technology assessment (TA) projects and to monitor and analyse important scientific and technological trends and the associated social developments (Monitoring, Future- and Innovation Reports, Policy-Benchmarking Reports).

Reinhard Grünwald

GREENHOUSE GAS – BURY IT INTO OBLIVION

OPTIONS AND RISKS OF CO_2 CAPTURE AND STORAGE

Report for the Committee on Education, Research and Technology Assessment

OFFICE OF TECHNOLOGY ASSESSMENT
AT THE GERMAN BUNDESTAG

NOTE

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Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag (TAB)
(Office of Technology Assessment at the German Bundestag)
Neue Schönhauser Straße 10
10178 Berlin
Germany

Fon: +49(0)30/28 491-0
Fax: +49(0)30/28 491-119
buero@tab-beim-bundestag.de
http://tab-beim-bundestag.de/

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THE COMMITTEE' S PREFACE

Over 80 % of Germany's energy supply is based on fossil energy carriers, use of which releases carbon dioxide (CO_2) into the atmosphere. Today, our economy has to import these crucial energy and raw-material sources. Yet, fossil raw materials as resources are finite and their availability is limited. To this must be added the fact that, according to the most recent UN climate study, today's consumption of fossil raw materials is crucially responsible for climate-damaging CO_2 emissions. Considered against this backdrop, the question must be asked as to how the capture of CO_2 from power plants and industrial facilities and its storage in deep geological layers can help us achieve ambitious climate-protection targets.

It was for this reason that the Committee on Education, Research and Technology Assessment of the Germany Bundestag took a decision in 2006 to instruct the Office of Technology Assessment at the German Parliament (TAB) to address the subject of »CO_2 Capture and Storage at Power Plants«. One aim was to survey the present state of knowledge and to identify critical knowledge gaps – e.g. as regards storage safety, costs, the availability of the technology. Another was to analyse the existing legal framework for CO_2 capture and storage (CCS) in order to detect possible deficits and any need for legislative action.

The report highlights the fact that, both in the technology for capturing the CO_2, and in its transportation to the storage site as well as its injection and permanent deposition in deep rock layers, there is still considerable need for research and development before the process is mature for commercial-scale deployment. Expert circles are agreed that this will take at least another 15 to 20 years. At the same time, the knowledge gaps still existing today, mainly as regards the behaviour of CO_2 below ground, must be closed before any robust assessment of a possible contribution of CCS to climate protection can be made. The demonstration and pilot projects required for this currently lack a legal basis, so that development of a suitable regulatory framework must be tackled. This is all the more true of any industrial-scale implementation of the technology at a later date.

In this report by the TAB, the German Bundestag is being given an updated and comprehensive information basis for further policymaking in shaping the framework conditions for a more sustainable energy supply.

Berlin, May 6, 2008

The Committee on Education, Research and Technology Assessment

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Dr Petra Sitte, Member of the German Bundestag
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Rapporteur

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SUMMARY

Carbon dioxide (CO_2) is inevitably produced when fossil fuels are used and is usually released into the atmosphere, where it affects the climate. One option for climate protection is to capture the CO_2 and isolate it permanently from the atmosphere. This is the principle of CO_2 capture and storage (CCS), a procedure that is primarily suitable for large, stationary CO_2 sources, e.g. electricity-generating power plants or certain industrial processes (e.g. manufacture of ammonia or cement). CCS is being discussed particularly in the context of coal-fired power plants, as these emit the highest amount of CO_2 in relation to electricity production. But CCS could in principle be an option for other fossil fuels, too. With the use of biomass, it is even conceivable that the CO_2 content in the atmosphere might even be actively reduced. Experts reckon that it takes about 15 to 20 years for CCS technology to reach large-scale maturity.

For an overall evaluation of whether CCS technology is compatible with the principle of a sustainable energy supply, the question of reducing greenhouse gases (GHGs) is not the only central topic. On the contrary, other criteria must be considered, in particular the conservation of exhaustible resources, economic efficiency and social factors, e.g. management of long-term risks in terms of intergenerational fairness and social acceptance.

STATE OF THE ART: THE NEED FOR RESEARCH

The CCS technology chain consists of three elements: *separation* of CO_2 in as concentrated a form as possible at the power plant, *transport* to a suitable storage site and actual *deposition* below the earth's surface.

CO_2 SEPARATION

There are three options for separating CO_2: (1) It can be filtered out of the flue gases after combustion; (2) the carbon can be removed from the fuel before the actual combustion process; or (3) combustion can be conducted in an oxygen atmosphere so that (practically) the only flue gas produced is CO_2. These three options are termed (1) *post-combustion*, (2) *pre-combustion*, and (3) *oxyfuel*. The feature common to all the above-mentioned processes for separating CO_2 is that they require a considerable expenditure of energy, which reduces the power-plant efficiency by up to 15 percentage points and results in an additional requirement of fuel that can reach 40 %. Each of these methods has specific advantages and disadvantages. Thus, it is still an open question which of them offers the best prospects for the future.

- The *post-combustion process* as a typical »end-of-pipe« procedure has the advantage of being potentially integrable into existing industrial processes and power plants. However, this advantage of possible retrofitting is offset by relatively high costs and energy losses. CO_2 separation using chemical absorption is currently the only commercially available procedure and is used, for instance, for natural gas processing. To be amenable for use in (large) power plants, it would have to be scaled up by a factor of 20 to 50. Further research and development efforts aim at increasing efficiency, particularly by further developing the solvents used, but also at improving process integration and optimizing its deployment in power plants. One interesting perspective could lie in innovative processes (e.g. membrane processes), since these promise greater efficiency and reduced costs. These are currently still at an early stage of research.
- The *pre-combustion process* in comparison has a lower energy requirement and offers the perspective of producing hydrogen or synthetic fuels from fossil fuels with relatively low CO_2 intensity. The disadvantage here, however, is the great complexity of the plants and their operation. Key components for the pre-combustion process are highly efficient hydrogen turbines. These are currently still at the pilot stage and must be significantly further developed before they can be put into commercial use. Progress in membrane technology could contribute to increasing the efficiency and economy of this process. Beyond the development of individual components, further significant challenges are the control of the process chain in its entire complexity on a real power-plant scale and the guarantee of a high level of availability for the whole plant.
- The *oxyfuel process* has the advantage that a relatively high concentration of CO_2 is present here, and the flue-gas stream to be processed is much smaller than for the other processes. The disadvantage of this process is that the production of pure oxygen is bound up with a high use of energy and with considerable expense. Air separation plants for producing oxygen have been in industrial use for some time now. The high energy consumption required for liquefying air, however, makes it seem necessary to significantly further develop this process or alternative methods for oxygen production (e.g. membrane technology). As with the other processes for CO_2 separation, integrating the individual steps of the process into an efficiently working overall system is a major task.

Post-combustion, pre-combustion and oxyfuel are processes that can be deployed in the short or medium term for CO_2 separation in power plants. In addition, research is being pursued into other alternative separation procedures, which in the long term promise considerable progress, especially with regard to energy requirements and costs. The feature common to these innovative processes is that they are all currently at the stage of conceptual studies and laboratory tests, and their use is only to be expected in 20 to 30 years at the earliest. Promising candidates here include the use of fuel cells, the so-called ZECA process and »chemical-looping combustion«.

CO_2 TRANSPORT

For transport, the CO_2 must be compressed after separation. The energy consumption required for this corresponds to a loss in power-plant efficiency of about 2-4 percentage points. For the large amounts produced in power plants (in a coal-fired power plant with electrical power of 1,000 MW about 5 $MtCO_2$/yr are produced), the most eligible means of transport are ships and pipelines. Transporting CO_2 in *pipelines* is in principle no different from transporting oil, gas and liquid hazardous substances, which is being done extensively worldwide. The biggest difference in CO_2 pipelines is that the materials used must be highly corrosion-resistant. Transporting CO_2 by *ship* is currently only used to a very limited extent; the technology is not essentially different from the conventional transport of liquid gas (liquefied petroleum gas, LPG). Transport by ship is above all suitable for great distances (more than 1,000 km) and amounts that are not too large.

Despite its important function as a link between capture and storage, CO_2 transport has so far been accorded little attention by research and – if at all – is mainly discussed in terms of cost. Important questions that should be addressed would include the temporal and geographic coordination of setting up a transport infrastructure, national or regional preconditions or barriers for this and questions of the acceptance of transport through densely populated areas.

CO_2 STORAGE

For the long-term geological storage of CO_2, depleted oil and gas fields and so-called saline aquifers are particularly worthy of consideration:

- *Oil and gas reservoirs* have the advantage that they have been shown to be enduringly impermeable over millions of years. Thanks to the exploration and exploitation of the repositories, the composition of the rocks and the structural layout of the storage and sealing formations are known very precisely. The biggest problem for storage safety is posed by old abandoned drill holes, which in some cases may be present in large numbers in oil and gas fields. Locating and, in particular, sealing off old drill holes is time-consuming and costly. The injection of CO_2 can if applicable be used for prolonging the extraction of oil or gas from almost depleted fields (so-called enhanced oil/gas recovery, EOR, EGR).
- *Saline aquifers* are highly porous sedimentary rocks which are saturated with a strong saline solution (brine). The space in their pores can be used for CO_2 intake, with some of the brine being displaced. For an aquifer to be suitable

as a CO_2 storage area, there must be a caprock above the aquifer that must be as CO_2-impermeable as possible. It has to be assured as far as possible that no CO_2 can escape along crevasses, rift zones or similar and that the brine cannot come into contact with groundwater near the surface.

STORAGE POTENTIAL

CO_2 capture and storage can only provide an appreciable contribution to climate protection if sufficient storage capacity is available to accommodate the separated CO_2. The range of current estimates for *worldwide* storage potential is enormous (from 100 to 200,000bn t CO_2), so that they are far too imprecise to allow any reliable estimate of the possible significance of CCS for global climate protection.

In *Germany*, several natural-gas fields are reaching the end of their production phase and would thus become available in principle in the next few years for storing CO_2. The overall storage capacity in aquifers and depleted natural-gas repositories together amounts to about 40 to 130 times the annual CO_2 emissions from German power plants (approximately 350 Mt/yr).

The question of whether this potential can be economically tapped for CO_2 storage and indeed be used is dependent on a number of geological details, on economic, legal, and political conditions, and on social acceptance. In addition, geological formations which are suitable for CCS are also interesting for alternative forms of use (e.g. geothermal energy, seasonal natural-gas storage). It is thus to be expected that the usable capacity for CCS in practical terms will be considerably smaller than the theoretical potential.

RISKS, ENVIRONMENTAL EFFECTS

The possibility exists all along the CCS processing chain that CO_2 will escape – with adverse effects both for the local environment and for the climate. Generally, the risk of technical plants (e.g. separation equipment, compressors, pipelines) is judged to be low or manageable with the usual technical means and controls. The discussion of risk thus concentrates on the geological reservoirs.

Still a matter of controversy is the minimum time that the CO_2 must remain underground for CCS to be able to make a positive contribution toward reducing GHGs in the atmosphere. The times discussed usually range from 1,000 to 10,000 years.

The most important processes which could compromise the safety and permanence of CO_2 storage according to the state of knowledge today are:

- geochemical processes, particularly the dissolution of carbonate rocks owing to the acidic CO_2-water mixture;
- pressure-induced processes, e.g. the expansion of existing small fissures in the caprock through the overpressure of CO_2 injection;
- leakage through existing drill holes, relevant particularly in oil or natural-gas repositories;
- leakage via unidentified migration pathways in the caprock (crevasses etc.);
- lateral expansion of the formation water, which is displaced by the injected CO_2.

General statements on the safety of particular storage types are only useful to a limited extent and do not suffice by any means for a decision to be made on a concrete CO_2-injection site. For this, each potential reservoir must be examined individually with regard to its specific features. To estimate risk profiles of geological reservoirs, it is urgently necessary for further studies and field experiments to be conducted.

The long-term safety of geological CO_2 repositories is not only a question of geological features. It is rather the case that appropriate regulation and continuous monitoring are necessary to guarantee a sufficient degree of knowledge so that storage risks can be minimised.

COSTS, COMPETITIVENESS

The costs of CO_2 separation and storage are made up of the costs for the individual process steps (separation, transport, and storage) together. In addition, the degree of loss in power-plant efficiency and the ensuing higher consumption of primary-energy sources must also be taken into account.

The dominant cost factor lies in the expenditure for CO_2 separation. Compared with a power plant of the same type but without CO_2 separation, the additional costs are estimated at between Euro 26/t and 37/t (in relation to the amount of CO_2 avoided). For coal-fired power plants this means almost doubling the cost of electricity generation, and for natural-gas combined-cycle stations it means an increase of 50 %. On the basis of the cost analyses available so far, no clear preference can be inferred for a particular technique (e.g. oxyfuel v pre-combustion). The costs of preventing CO_2 by means of CCS in coal-fired power plants – assuming introduction onto the market in around 2020 – amount approx. to between Euro 35/t and just under Euro 50/t CO_2, while they are significantly higher for natural-gas power plants.

CCS technology will only be deployed on the electricity market if it is competitive with other production options. The prerequisite for this is that production of climate-friendly electricity is rewarded. In other words, the price for CO_2

emissions, such as is determined on the European market for CO_2-emission certificates (EU allowances, EUA), must be set at least so high that CCS power stations can compete with fossil-fuel power plants without CO_2 separation. In the light of the above-mentioned CO_2-separation costs, this would mean a price of about Euro 30 to 40/EUA.

A comparison of electricity-generation costs in CCS power plants with other low-CO_2 and especially regenerative production methods shows that, in the year 2020, most of the regenerative technologies that have been examined could have reached a cost level similar to that calculated for CCS power stations (in range of Euro 0.05 to 0.07/kWh). Although the prognostic power of such long-term projections should not be overrated, it seems incontestable that CCS will not have the field to itself, but will have to compete with other technologies for low-CO_2 electricity generation.

INTEGRATION INTO THE ENERGY SYSTEM

In Germany, the age structure of the power plants means that in the next two to three decades there will be considerable need for renewals. The contribution that can be made by CCS technology toward reducing CO_2 against this background depends strongly on the answers to the following questions:

> When will CCS really be available?
> Is it feasible to retrofit existing power plants with CCS technology?
> Is it a tenable idea to prepare the new power plants being built now to make them fit for later retrofitting (i.e., to make them »capture-ready«)?

Since effective climate protection can only be addressed globally, CCS should also be evaluated from an international perspective.

TIMEFRAME FOR AVAILABILITY

In various papers on research strategy, as well as roadmaps, one topic is the projected time in which CCS technology could be available. A common feature of most of these publications is that 2020 is cited as the target year for commercial availability on a power-plant scale. Among experts, though, this is regarded as very ambitious. One reason for the brief time period could be the recognition that the contribution that CCS can make to CO_2 reduction becomes increasingly smaller, the longer it takes to make the technology fully available. A look at the currently initiated projects or planned pilot and demonstration projects reveals that it only seems possible to keep to the stated timeframe if the economic and political conditions are favourable.

POTENTIAL RETROFITTING/»CAPTURE-READY«

In principle, existing power plants could be retrofitted with CO_2 separation equipment. Post-combustion with subsequent flue-gas scrubbing involves the least technical effort and means the smallest amount of intervention in the power-plant process itself. The question of whether power plants really will be retrofitted depends not only on technological feasibility, but crucially on economic viability. Retrofitting power plants is costly and as a rule more expensive that integrating CO_2 separation into a new plant. It is to be assumed that retrofitting would only be conducted on a larger scale if the economic incentives for CO_2 separation are high enough or if, for example, an obligation to upgrade were introduced.

At first glance, the idea of preparing new power plants today in such a way that they can be retrofitted later with CO_2-separation systems in a technically uncomplicated and cost-effective way, as soon as the technology and corresponding CO_2 repositories are available, looks like a plausible and attractive proposition. This *»capture-ready« concept* is currently the subject of much discussion among experts, especially since the EU Commission floated the suggestion that fossil fuel-fired power-plant approvals be confined in future to those that are capture-ready. However, the options for installing capture-ready components in the power plants to be built today are extremely limited.

From today's perspective, only those measures would be economically acceptable that involve only little cost, e.g. provision of a site for building the CO_2-separation plant and maintaining ready access to components which would probably have to be upgraded or replaced in the course of retrofitting. Another factor worth careful attention is the siting of power plants so that they are found close to a potential repository or to existing infrastructure for CO_2 transport.

For a robust estimate of whether the capture-ready concept is acceptable, there is still a considerable need for technical-economic analyses. In addition, criteria must be developed which, for example, permit approval authorities to judge the capture-readiness of power plants.

INTERNATIONAL/GLOBAL PERSPECTIVES

CCS technology could be particularly attractive for countries which have so far been sceptical about climate-protection measures (e.g. USA) and/or want to continue to use their domestic primary-energy basis of fossil fuels (especially coal; e.g. China, India).

In China alone, between 1995 and 2002 about 100,000 MW of fossil fuel power-plant capacity (primarily coal-fired power plants) was built. For the period 2002 to 2010, it is forecast that a further 170,000 MW will be added. If this trend were allowed to progress unchecked, the success of international climate-protection efforts would be seriously imperilled.

For the deployment of CCS technology to become an attractive option in these and other emerging nations, it would first have to be successfully further developed and proven. The most suitable candidates for this are industrial countries with their technical know-how and financial resources. In the face of the dynamics of power-plant expansion, however, CCS would have to be introduced as quickly as possible, since otherwise the window of opportunity would close again and might remain closed for many decades.

PUBLIC PERCEPTION AND ACCEPTANCE

Public perception can have considerable and unexpected effects on planned technological and infrastructure projects. Other disputes – especially with regard to atomic energy and genetic engineering – are a clear illustration of this. Technologies like CCS whose long-term risks to our safety, health and the environment are hard to assess are particularly prone to triggering public unrest and possibly resistance.

Hence, ensuring a high degree of public acceptance should be a high-priority goal from the very beginning. One important prerequisite for acceptance is the creation of transparency by providing comprehensive information both about the aims of CCS in general and about concrete intentions and projects. As the past has shown, however, measures relying purely on information and advertising are by no means sufficient to create acceptance. To avoid crises of acceptance and trust, an open-ended process of dialogue should be initiated between industry, stakeholders, science and the public at an early stage.

LEGAL ISSUES

For the testing, introduction and diffusion of CCS technology, a suitable regulatory framework must be created which should have three simultaneous goals: first, establishing the conditions for the *admissibility* of the various components of CCS technology (separation, transport, storage); second, providing *incentives* for investing in CCS technology; and third, guaranteeing that CCS does not fail for lack of public *acceptance* in general and at the storage sites in particular.

Under current law, no procedure exists either for *exploring locations* to identify repositories or for the *storage* of CO_2. Creating an adequate regulatory framework means a double challenge. If it is assumed, on the one hand, that the rapid introduction of CCS on an industrial scale is in the public interest for the sake of climate protection, then it will be necessary, on the other, to authorize initial CCS projects at short notice in order to gain experience with the technology.

This experience is necessary both for the further development of the technology and for political and legal guidance. In Germany, several companies already have concrete plans with this aim in mind, and some plans are at an advanced stage. The planned projects will be inadmissible, however, if the law as it stands is not amended in the short term.

All the same, a regulatory concept should preferably take all the relevant factors into account: selective use of the limited number of storage facilities available, consideration of competing claims for use, questions of liability, creating transparency, regional-planning challenges, integration into the climate protection regime, etc. Although a regulatory concept of this kind would greatly contribute to promoting acceptance and avoiding conflict, this would require sufficient time for its elaboration, discussion, decision-making, and realization.

NEED FOR ACTION

On the basis of the current state of our knowledge and assuming there is public interest in the deployment of CCS technology to promote climate protection, the TAB assesses that the following factors should be given priority.

BROADENING THE KNOWLEDGE BASE: CLOSING CRITICAL GAPS IN OUR KNOWLEDGE

Current knowledge is too inadequate by far to permit any robust assessment of the technical and economic feasibility of CCS or any evaluation of the contribution that CCS can make toward achieving climate targets. For that, numerous critical gaps in our knowledge must be closed.

With regard to research and development in the field of *CO_2 separation* and the technologies for *CO_2 conditioning and transport*, the onus is on industry as the primary actor (power-plant and equipment construction, utilities, chemical industry). The main task for state actors in this context would be to maintain or create a reliable environment so that companies could fully develop the socially desired research initiatives. The fields of action that offer the most promising candidates for justifying the public funding of research would be highly innovative procedures with great potential for public benefit, whether ecological and economic, and cross-section fields (e.g. materials research).

The greatest deficit in our knowledge and the greatest need for research is currently in the area of geological *CO_2 storage*. In this field, there is also a special need for state action. Questions which would represent particularly good candidates for publicly funded research projects would include the interaction of injected CO_2 with rock formations, the determination of storage capacity, and investigations into the suitability of geological traps for the long-term storage of

CO_2. There is an urgent need for research in the field of possible competition from alternative uses (natural-gas storage, geothermal energy). This also includes the question of how to resolve any usage conflicts (e.g. priority rules).

An urgent recommendation is that accompanying research in the social and environmental sciences be integrated into pilot projects at an early stage in order to ensure that technological development can be geared to the criteria of sustainable development and that knowledge about the economic, ecological and social effects of CCS needed for later decisions will be available. This includes the analysis of potentials, risks, and costs, considerations of lifecycle assessment and questions of integrating CCS into the energy system.

TRIGGERING A PUBLIC DEBATE

To prevent a lack of acceptance from becoming an obstacle to further development and to the use of CCS technology, a national strategy of communication, information, and participation should be designed and implemented at an early date. This process should be structured so as to leave the outcome open and should sound out whether and how the broadest social consensus possible can be achieved. This is a demanding task which should be initiated before the first concrete siting decisions are to be made. A first possible step in organising this process of communication, namely the establishment of a national »CCS forum«, is being put forward for discussion, and this could bring together all the relevant stakeholder positions in Germany.

CREATION OF A REGULATORY FRAMEWORK

There are several companies in Germany that are already planning concrete CCS projects, some of which are at an advanced stage. However, without early amendments to the current law, these planned projects will be inadmissible. Thus there is urgent need for action here.

A two-step procedure would be ideal: in the course of an interim solution, which should be realised in the short term, the legal preconditions should be created so that projects mainly concerned with research and the testing of CO_2 storage can be promptly initiated. The central element in a short-term regulatory framework would be the creation of an approval fact (*Zulassungstatbestand*) in mining law.

At the same time, a comprehensive regulatory framework should be developed and if possible coordinated at EU level and internationally which accommodates all aspects of CCS technology. This could supersede the interim regulation as soon as CCS is available for large-scale technical deployment.

INTRODUCTION I.

»The current energy system is unsustainable.« This was the unanimous finding of the Study Commission on »Sustainable Energy Supplies in View of Globalization and Liberalization« set up by the 14^{th} German Bundestag. This assessment is crucially based on the recognition that the provision and use of energy as practised today ignores environmental costs on a grand scale, overexploits scarce resources and pays too little heed to risk aspects (EK 2002).

Over 80 % of Germany's and the EU's present energy supply is based on finite fossil energy sources (coal, oil, gas). Using these produces CO_2, which contributes to man-made climate change. In the EU-25, if current trends go unchecked, primary-energy consumption is expected to rise some 20 % by 2020 compared with 1990. The consumption of fossil fuels is forecast to increase by approx. 10 %. Although coal's importance will fall substantially, this will be more than compensated by soaring natural-gas consumption, so that CO_2 emissions would grow by 4 % (relative to 1990) as a result (EU Commission 2006).

In Germany and Europe, there is now broad acceptance of the goal of lowering greenhouse-gas (GHG) emissions in the EU and worldwide so as to limit the global temperature rise to 2°C compared with pre-industrial levels (Federal Government 2006; EU Commission 2007a). This would require industrialized countries to reduce emissions by at least 30 % or so by 2020.

In Germany and in the EU, it might be possible to achieve such an ambitious reduction target if a comprehensive climate-protection strategy were systematically implemented, inter alia by redoubling our efforts on behalf of improved energy efficiency, stepping up the expansion of renewable energies and substituting carbon-intensive energy sources (e.g. coal with gas). However, this only appears to be realistic if political efforts are made that go well beyond what is usual today (Prognos/EWI 2007). At international level, some countries are voicing the concern that the measures required and the associated costs might hold back economic and social development.

Viewed against this background, the question arises as to whether the separation of CO_2 from the flue-gas stream of power plants and its underground deposition (carbon-dioxide capture and storage, CCS) might not be one way to achieve the ambitious climate-protection targets. Research and trialling as well as the debate surrounding CCS technology have been ongoing at European and international level for some time now. At present, three major CCS projects (involving over 1 $MtCO_2$ per year) are in operation worldwide: »Sleipner« in Norway, »Weyburn« in Canada and »In Salah« in Algeria. Others are being planned. In Germany, such activities have only in recent times appeared on radar screens (above all CO_2SINK in Ketzin near Potsdam).

For these reasons, the Committee on Education, Research and Technology Assessment of the German Parliament decided in summer 2006 to charge the TAB with addressing the issue of »CO_2 Capture and Storage at Power Stations«. The aim was, on the one hand, to enhance the current state of knowledge and to identify critical knowledge gaps – e.g. as regards storage safety, costs, availability of the technology – and, on the other, to analyse the existing legal framework for CCS to detect any deficits and need for legislative action. Also to be examined was the current perception and acceptance of CCS technology in specialist circles and in the public.

Accordingly, the report has the following structure: Chapter II describes the present development status of CCS technology (carbon-dioxide capture, transport and deposition/storage), and contains an overview of existing research and development needs. This Chapter has been deliberately kept brief, since a range of publications is already available on the subject. Particular mention should be made of a recent publication of the Scientific Services of the German Bundestag (WD 2006). The quantity potentials for storing CO_2 in geological formations as well as their risks and costs are analysed in Chapter III. Chapter IV examines the prospects for integrating CCS power plants into the energy system in view of current underlying energy-policy conditions, e.g. the need to renew the power-plant fleet. It also thematizes the retrofitting of existing power stations with CCS systems and asks what options there are for so-called »capture-ready« power plants. Public perception of CCS technology is examined in Chapter V, as are the prerequisites and possibilities for developing the social acceptance of this technology. One focus of this report is on law and regulation (Chapter VI). Proceeding from a deficit analysis of the current legal framework, concrete options are identified for ensuring the legal permissibility of CCS, providing incentives for its implementation and boosting social acceptance. Finally, the report identifies the need for action that exists in view of today's state of knowledge and development, as assessed by the TAB.

This report is largely based on the following expertises commissioned within the scope of the project:

- Dr M. Jung, C. Kleßmann (Ecofys Germany GmbH): CO_2-Abscheidung und -Lagerung bei Kraftwerken (CO_2 capture and storage at power plants);
- Dr F.C. Matthes, J. Repenning, A. Hermann, R. Barth, F. Schulze, M. Dross, B. Kallenbach-Herbert, A. Minhans with the collaboration of A. Spindler (Öko-Institut e.V.): CO_2-Abscheidung und -Lagerung bei Kraftwerken – Rechtliche Bewertung, Regulierung, Akzeptanz (CO_2 capture and storage at power plants – Legal assessment, regulation, acceptance);

- Dr C. Cremer, S. Schmidt (Fraunhofer-Institut für System- und Innovationsforschung): Modellierung von Szenarien der Marktdiffusion von CCS-Technologien (Modelling of scenarios for the market diffusion of CCS technologies).

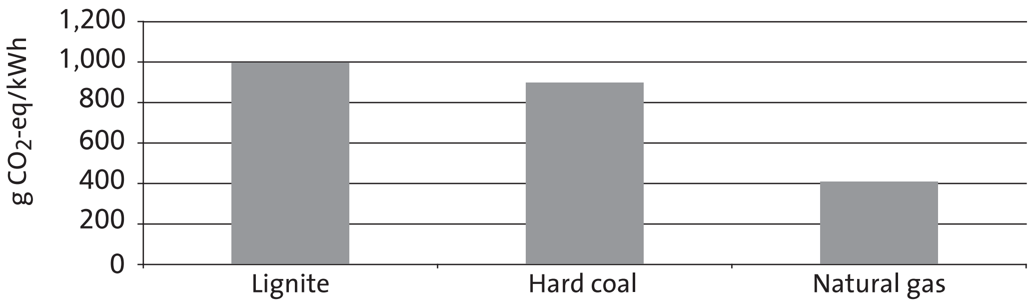
The remarks in the running text will indicate the specific expertises to which the various chapters refer. Responsibility for selecting and structuring the information they contain and for combining this with findings from other sources lies with the author of the report. At this point, an express word of gratitude again goes to the experts for the results of their work, their excellent and always agreeable cooperation and unstinted willingness to discuss the subject matter at hand.

A cordial word of thanks is also due to the participants in the workshop of experts mounted by the TAB and held in Berlin on 18.01.2007. With their contributions to the debate and their suggestions, they have delivered invaluable input for the production of this report: Dr S. Asmus (RWE Power AG), M. Blohm (Umweltbundesamt, UBA), Prof Dr G. Borm (GeoForschungsZentrum Potsdam, GFZ), Dr R. Brandis (BP AG), Dr L. Dietrich (Osnabrück), Dr O. Edenhofer (Potsdam-Institut für Klimafolgenforschung, PIK), Dr J. Ewers (RWE Power AG), Dr J.P. Gerling (Bundesanstalt für Geowissenschaften und Rohstoffe, BGR), Dr G. von Goerne (Greenpeace e.V.), S. Hagedoorn (Ecofys Netherlands BV), Dr W. Heidug (Shell International Renewables B.V.), Dr H. Held (Potsdam-Institut für Klimafolgenforschung, PIK), S. Lüdge (Vattenfall Europe Generation AG & Co. KG), Dr P. Markewitz (Forschungszentrum Jülich), Dr P. Radgen (Fraunhofer-Institut für System- und Innovationsforschung, ISI), K. Stelter (Deutscher Braunkohlen-Industrie-Verein e.V., DEBRIV), Dr B. Stevens (Vattenfall Europe Generation AG & Co. KG), Dr P. Viebahn (Deutsches Zentrum für Luft- und Raumfahrt, DLR), Dr M. Vosbeek (Ecofys Netherlands BV).

Sincere thanks are due to Dr Thomas Petermann whose keen eye and constructive comments have made a crucial contribution to the stringency and readability of this report. Last but not least, I wish to thank Dr Katrin Gerlinger and Dr Christoph Revermann for proofreading the drafts as well as Ms Ulrike Goelsdorf and Ms Gaby Rastätter for their support in producing the final layout.

Carbon dioxide (CO_2) is inevitably produced when fossil fuels are used and is usually released into the atmosphere, where it affects the climate. The basic idea behind CO_2 capture and storage (CCS) is that the CO_2 should be captured and isolated from the atmosphere permanently. This technology is mainly suitable for large, so-called point sources which produce CO_2 on a scale of millions of tonnes a year. Such sources are mainly electricity-generating power plants. In addition, CCS is also an interesting option for various industrial processes, as CO_2 is produced here in a relatively concentrated form, e.g. in the manufacture of ammonia or cement. CCS technology is not suitable, by contrast, for plants that produce only relatively little CO_2 (e.g. heating systems in buildings), or mobile sources (e.g. vehicles).

FIG. 1 CO_2 INTENSITY OF SELECTED POWER GENERATION SYSTEMS



Lignite: steam power plant η = 43 %, lignite, Rhineland
Hard coal: steam power plant η = 45.5 %, hard coal, GER
Natural gas: gas and steam combined-cycle plant η = 57.6 %, gas mix, GER

Source: own illustration, data from Marheineke 2002, p. 180

The amount of CO_2 that is released per unit of useful energy (i.e. the CO_2 intensity) depends on the type of energy source (most of all on its carbon content) and the efficiency of the conversion processes (Fig. 1; on this, see also WD 2007). Hence, in coal-fired power plants, much more CO_2 is emitted relative to the amount of electricity generated than in gas-based power stations. This being so, CCS is mainly being discussed for coal-fired power plants. All the same, the CO_2-reduction potentials of CCS for gas-based power stations should not be ignored. Where biomass is used as fuel, an active reduction in the CO_2 content in the atmosphere might even be feasible in the long term.

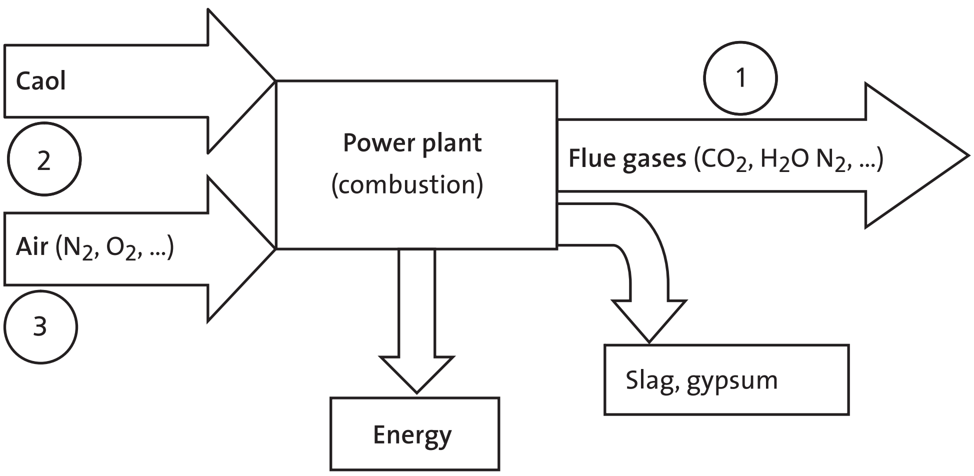
The CCS technology chain consists of three steps: *capture* of the CO_2 in as concentrated a form as possible at the power plant, its *transport* to a suitable storage site and underground *deposition*[1].

One important basis for the following account is the expert report commissioned by the TAB (Ecofys 2007).

CO_2 CAPTURE 1.

The process diagram in Figure 2 shows the three possibilities for capturing carbon dioxide at a (coal-fired) power plant.

FIG. 2 PROCESS DIAGRAM OF A COAL POWER PLANT



Source: own illustration

It can (1) be filtered out of the flue gases after combustion; (2) the carbon can be removed from the energy source before the actual combustion process; or (3) combustion can be in an oxygen atmosphere so that (practically) the only flue gas produced is CO_2. These options are referred to as (1) post-combustion, (2) pre-combustion, and (3) oxyfuel.

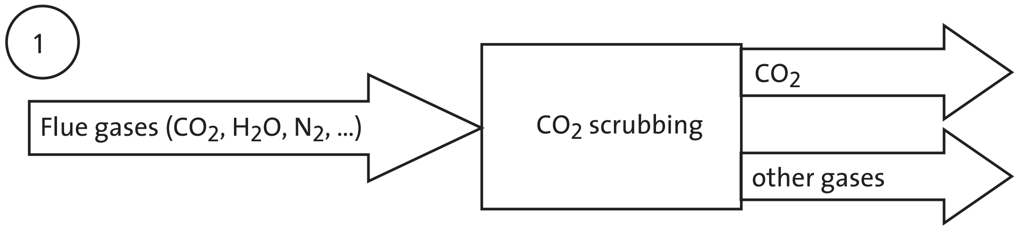
1 The literature uses a whole host of different terms, like storage, sequestration, deposition, injection into a reservoir, etc., each of which has its own connotations and underscores specific aspects. In our view, the term »storage« used here best expresses the intention of long-term isolation. A specification, in the sense of legal operative facts, say, is not intended here.

POST-COMBUSTION 1.1

OPERATION

In the post-combustion process, the CO_2 contained in the flue gas is captured by gas separation (Fig. 3).

FIG. 3 CO_2 SEPARATION AFTER COMUBSTION



This flow diagram follows on from arrow (1) in Fig. 2.

Source: own illustration

The most usual method is chemical absorption in which the CO_2 is bound in a liquid solvent (normally monoethanolamine, MEA). In a next step, the solvent is regenerated by using heat to drive off the CO_2. This is associated with considerable energy outlays. Other ways, too, can in principle be used in CO_2 capture, inter alia, surface-treatment techniques (e.g. adsorption onto activated carbon), cryogenic processes and membranes.

ADVANTAGES/DISADVANTAGES

CO_2 flue-gas scrubbing is a downstream method, so that it can, in principle, be integrated into existing industrial processes and power plants as well. However, the advantage of retrofitability must be juxtaposed with relatively high costs and energy losses. Also, there are considerable space requirements for the separation systems. When conventional coal-fired power stations are retrofitted, we must expect efficiency losses of 8 to 14 percentage points[2], a 10 to 40 % increase in fuel needs and additional investment costs of between 20 to 150 % (IPCC 2005, p. 169; WI/DLR/ZSW/PIK 2007, p. 48).

2 For example, a power station with an initial efficiency of 43 % would merely have an efficiency of between 29 to 35 % when retrofitted with a CO_2 separation system.

STATE OF THE ART/RESEARCH NEEDS

Chemical absorption is currently the only commercially available process for separating CO_2, and it is used on a large scale, e.g., in processing natural gas. For it to be deployed in power plants, however, it must be scaled up 20 to 50 times due to the huge volume flow and the low CO_2 content of the flue gases (ETP ZEP 2006a, p. 13).

Future increases in efficiency can be expected mainly from the further development of the solvents employed. A rise in their stability against ageing and degeneration processes (caused e.g. by contaminants and residual oxygen in the flue gas) is another important research aim. Other key R&D areas in flue-gas scrubbing are process integration and optimization for deployment in large-scale power plants.

In future, adsorptive, cryogenic and membrane processes, too, could become interesting propositions, since they (and membrane processes in particular) promise greater efficiency and lower costs. At the moment, these processes are still at an early research stage. For a detailed overview of the state of research and further research needs, see, e.g., ETP ZEP (2006a, pp.12 ff.).

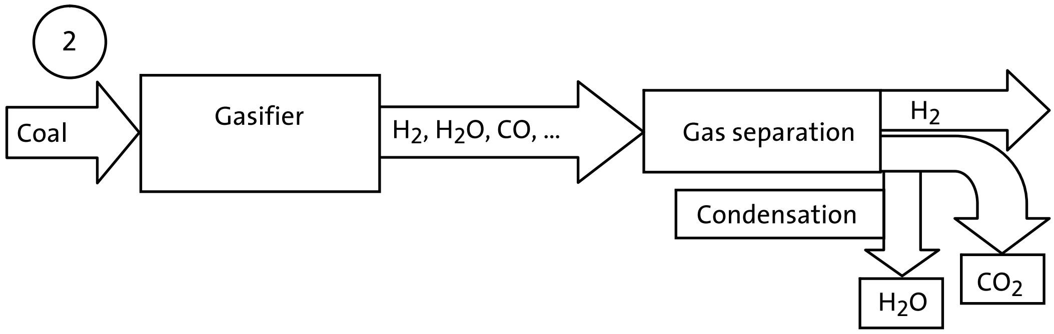
PRE-COMBUSTION 1.2

OPERATION

In an upstream step, the pre-combustion process produces hydrogen from the carbonic energy source for subsequent use in the power station; water vapour emerges as the only combustion product. In principle, this process is fuel-independent, although it is especially suitable for IGCC coal-fired power plants[3]. Here, a gasifier converts the coal into a mix of hydrogen and carbon monoxide (so-called »synthesis gas«). In a catalytic reactor (so-called »shift converter«), the carbon monoxide is converted into carbon dioxide and more hydrogen in a reaction with water vapour. In a next step, the CO_2 can be separated, e.g. by physical adsorption or membrane techniques.

3 Integrated gasification combined cycle, IGCC: these are gas and steam combined-cycle power plants with integrated coal gasification.

FIG. 4 **CO_2 SEPARATION BEFORE COMBUSTION**



This flow diagram follows on from arrow (2) in Fig. 2.

Source: own illustration

ADVANTAGES/DISADVANTAGES

The process of separation before combustion has the advantage that the gas to be processed is under pressure and is not diluted with nitrogen. This lowers energy consumption and the technological requirements to be met by CO_2 separation, compared with the post-combustion concept. One drawback, however, is the greater complexity of IGCC power stations, which has led to problems with plant availability in the past. What is more, CO_2 separation adds a further element to what is already a complex process.

The method offers the perspective of producing hydrogen from fossil fuels with relatively low CO_2 intensity. This hydrogen could also be used, e.g., in highly efficient fuel cells to produce electricity or as fuel in vehicles. Another option is to deploy the synthesis gas to make synthetic fuels.

STATE OF THE ART/RESEARCH NEEDS

IGCC (without CO_2 capture) is not a new technology. The first pilot plant dates back to 1984, and five IGCC power stations are now in operation worldwide. Nevertheless, such plants have been unable to gain a foothold on the market to date (BINEinfo 2006).

Highly efficient hydrogen turbines optimized for CCS and required for the pre-combustion process are still being piloted (ETP ZEP 2006a). Their urgent further development is regarded as crucial for the commercial deployment of the pre-combustion technology chain.

Advances in membrane technology could contribute to raising the efficiency and economy of this process. Here, too, there is a need for process optimization and up-scaling to make the method commercially deployable at a large plant.

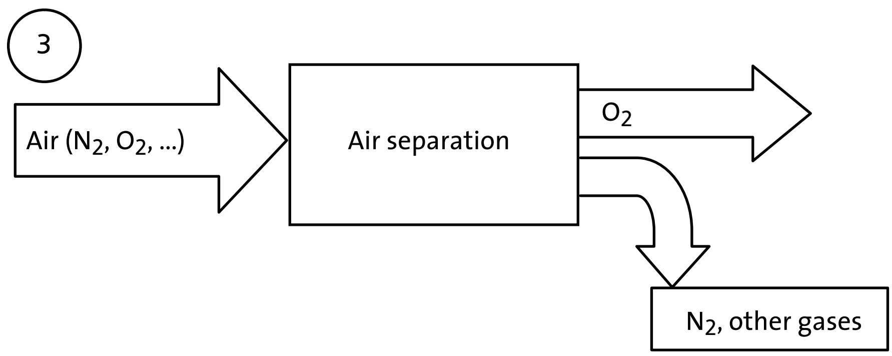
Beyond the development of individual components, one major challenge involves mastering the process chain in its entire complexity on a real power-plant scale and ensuring high availability of the station as a whole. This aim is also being pursued in the project planning of the company RWE Power: it is seeking to commission a 450-MW_{el} IGCC power plant with CO_2 capture and storage by 2014 (RWE 2007).

OXYFUEL PROCESS 1.3

OPERATION

In the oxyfuel process, combustion is in virtually pure oxygen. This produces less flue gas, on the one hand, and a high CO_2 concentration in the flue gas, on the other (over 70 %). The oxygen required for this must be made available by air separation (air liquefaction with subsequent distillation or, more precisely: rectification).

FIG. 5 OXYFUEL PROCESS



This flow diagram follows on from arrow (3) in Fig. 2.

Source: own illustration

As oxygen combustion is associated with very high combustion temperatures and, hence, involves potential material problems, some of the CO_2-rich combustion gas is returned to the combustion system to reduce the temperature of the flame.

ADVANTAGES/DISADVANTAGES

Thanks to the high CO_2 concentration in the flue gas, the costs of CO_2 separation fall. The drawback in this process is that the production of pure oxygen is associated with high energy consumption and considerable expense. In addition, the concentration of contaminants in the CO_2 is relatively high, so that (depending on the requirements to be met by the purity of the CO_2 for transport and storage) post-treatment may be necessary (Yan et al., no date).

STATE OF THE ART/RESEARCH NEEDS

Air-separation systems to produce oxygen have been in industrial use for some time now. However, the high energy consumption involved in air liquefaction points to a need for significant further development of this process or of alternative methods for producing oxygen (e.g. membrane technologies).

One aim of further research is the optimization of the combustion process in oxygen. There is likewise need for investigation of permissible contaminants and, in general, the processing of the CO_2-rich flue gas (ETP ZEP 2006a, pp. 17 f.).

The energy utility Vattenfall is currently building a 30-MW_{th} pilot plant that is due to be commissioned in 2008. A next step would be the erection of a demonstration plant in a size typical of a power plant (several 100 MW_{th}). In the oxyfuel method, too, process integration of the various elements has an important role to play if the technology is to be deployed on a commercial scale.

INNOVATIVE CO_2-SEPARATION PROCESSES 1.4

Post-combustion, pre-combustion and oxyfuel are processes for CO_2 separation at power plants that can be deployed in the short to medium term. Besides these, alternative separation methods, too, are being researched that promise important advances in the long term, chiefly as regards their energy requirements and costs. What these innovative processes have in common is that they are at the stage of conceptual studies and laboratory trials, so that deployment can be expected in 20 to 30 years' time at the earliest. Promising candidates for innovative separation processes include the utilization of fuel cells, the so-called ZECA process as well as chemical-looping combustion (CLC).

FUEL CELLS

One interesting option is the use of solid oxide fuel cells (SOFC) in power generation. The electrolyte of this fuel-cell type is an oxygen-permeable ceramic (usually doped zirconium dioxide), so that the separation of oxygen and nitrogen already takes place internally without any special measures. Hence, the flue gas (on the anode side) only contains CO_2 and unreacted fuel gas, which can be post-oxidized, with additional energy extracted, in a burner (water gas shift membrane reactor, WGSMR). The H_2 membrane contained in the WGSMR ensures that here, too, CO_2 is produced in a concentrated form.

The energy yield of this system can total more than 60 %. Compared with conventional systems, about half of the energy outlays are saved in CO_2 separation (incl compression) (Jansen/Dijkstra 2003). The development status of this technology is currently at the level of conceptual studies. Use in power plants is not expected before 2030 (WI/DLR/ZSW/PIK 2007, p. 58).

ZECA PROCESS

The ZECA process (named after the »Zero Emission Coal Alliance« and its successor »ZECA Corporation« resp.) gasifies coal (to form CH_4 and H_2), and calcination extracts carbon from this intermediate product (in a $CaO/CaCO_3$ cycle). As a result, hydrogen and CO_2 emerge in separate flows. The hydrogen can then be used, e.g. in a high-temperature fuel cell, to generate power. In this process, many technical issues are still unclear. If today's technologies are used, an efficiency of »only« 39 % is reached (WI/DLR/ZSW/PIK 2007, p. 59) with this concept. The efficiency in an order of 70 % achievable in theory when converting coal into electricity justifies further research (Ziock *et al.*, no date).

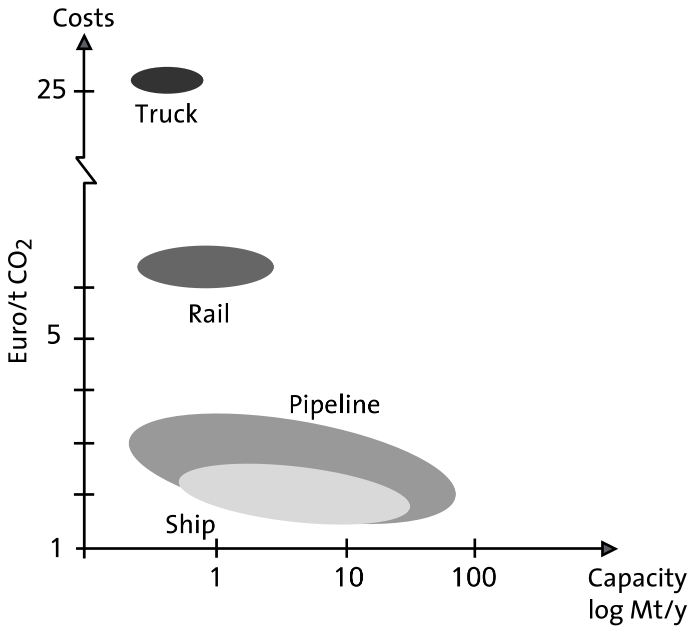
CHEMICAL-LOOPING COMBUSTION

This process for the oxidation of the carbonic fuel does not use oxygen directly, but a metal oxide (MeO) (e.g. Fe, Cu, Ni, Co). This produces CO_2 and the metal (Me). In a second step, the latter reacts with air to become MeO again, thus completing the Me-MeO cycle. The basic idea here is to spatially separate the two partial reactions during combustion (oxidation of the fuel and reduction of the oxygen), to obtain a separation of the combustion products (mainly CO_2 and water) from the remainder of the flue gases (e.g. N_2 and residual oxygen) (IPCC 2005, p. 129). The research efforts focus on the development of an oxygen carrier that is capable of coping with the constant oxidation/reduction cycle and is resistant to physical and chemical degradation (WI/DLR/ZSW/PIK 2007, pp. 60 f.). So far, 100 hours of operating experience have been clocked in a first pilot plant with 10 kW capacity (Lyngfelt/Thunman 2005).

TRANSPORT 2.

Since CO_2 capture and storage will usually be separate geographically, transport is an important element in the technology chain. In principle, CO_2 can be transported by pipeline, ship, rail or truck. For the large amounts produced in power plants – a power station with 1,000 MWe produces some 5 $MtCO_2$ per year – rail and truck are not an option due to their low capacity and prohibitively high costs (Fig. 6).

FIG. 6 **TRANSPORT CAPACITY AND COSTS**



assumed transport distance: 250 km

Source: FhG-ISI/BGR 2006, p. 63, data from Odenberger/Svensson 2003

Prior to transportation, the CO_2 must first be compressed after capture. For shipping, the liquid state (e.g. -48°C, 7 bar) is best suited; in the case of pipelines, the supercritical state[4] lends itself (FhG-ISI/BGR 2006, pp. 63 ff.). Owing to the energy consumption for this, the efficiency of the overall process falls by 2 to 2.7 percentage points for gas-fired and 3 to 4 percentage points for coal-based power plants (Göttlicher 2003)[5].

Transporting CO_2 by *pipeline* is not fundamentally different from transporting crude oil, natural gas and liquid hazardous substances by pipeline, which is a wide-spread practice globally. The biggest difference in the case of CO_2 pipelines is the need to consider high corrosion resistance when selecting the material. In the US, over 2,500 km of pipelines already transport more than 40 MtCO_2 per year, mainly for the purpose of »enhanced oil recovery (EOR)« (see below).

CO_2 transport by *ship* is on only a small scale at present; the technology involved is not basically different from the conventional transport of liquid gas (liquefied petroleum gas, LPG) (IPCC 2005, p. 30). Shipping is usually suitable

4 A special aggregate state is referred to as »supercritical« if the liquid and gaseous phases cannot be distinguished. CO_2 is supercritical above 31°C and 73 bar. Its density is then roughly in the range of liquid water.

5 In the literature the outlays for compression are usually allocated to the power plant and not to the transport system.

for greater distances (more than 1,000 km) and for amounts that are not too large.

ENVIRONMENTAL ASPECTS/RISKS

One relevant environmental aspect of pipeline transportation is the risk of leakages. Although CO_2 is not toxic, it can lead to death by asphyxiation upward of a concentration of 10 % by volume. Since CO_2 is heavier than air, it could accumulate, e.g., in hollows (sinks), thus constituting a danger to living beings. The overall hazard, however, has been assessed by US approval authorities as being low (classification: »High Volatile/Low Hazard and Low Risk«) (FhG-ISI/BGR 2006, p. 68). Safety aspects and public acceptance must be taken into account above all in the case of pipeline transport through densely populated regions. An impact on the environment from pipeline construction itself must be considered, especially if pipelines are to be laid through ecologically sensitive areas (UCS, no date, p. 9).

INFRASTRUCTURE

If CCs is to be used one a large scale, an extensive infrastructure for CO_2 transportation would have to be built up in the next few decades. With increasing market penetration, the initial 1:1 ratios between power plants and CO_2-storage areas would probably dissolve successively, and networks would grow (VGB 2004, p. 105).

The geographical location of sources and reservoirs is not only relevant for planning the transport infrastructure, but could emerge as an additional factor (besides fuel supply, access to cooling water and to the electricity grid) in siting decisions on new power stations and industrial facilities (Duckat et al. 2004, p. 17).

RESEARCH NEEDS

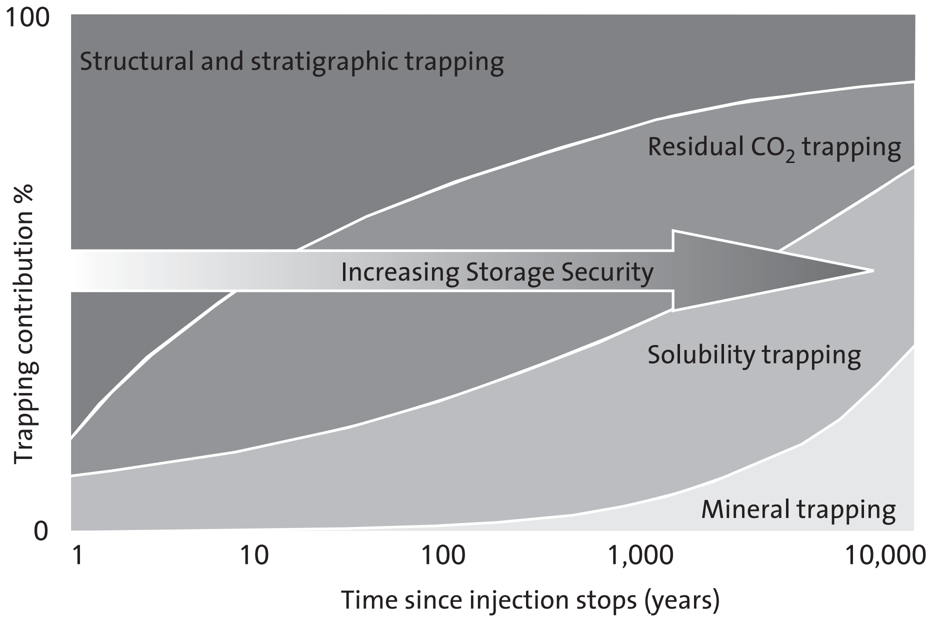
Despite its important function as a link between capture and storage, CO_2 transport has so far been largely ignored (FhG-ISI/BGR 2006, p. 63) by research and is mainly discussed – if at all – in terms of cost. Important issues to be addressed would include the temporal and geographic coordination of setting up a transport infrastructure with capture facilities and storage areas, questions of acceptance of transportation through densely populated areas and national or regional conditions or barriers for the creation of a transport infrastructure. With few exceptions, though, further technical developments are not the crucial consideration. One such exception, for example, would be the question of what technical requirements the transport infrastructure must meet if the CO_2 is chemically contaminated.

CO_2 STORAGE 3.

GEOLOGICAL STORAGE – MECHANISMS AND OPTIONS 3.1

The aim of geological storage is to trap the CO_2 underground for as long as possible, thus isolating it from the atmosphere. To do this, a range of geological, (geo)physical and (geo)chemical mechanisms is being used.

FIG. 7 CONTRIBUTION BY STORAGE MECHANISMS OVER TIME

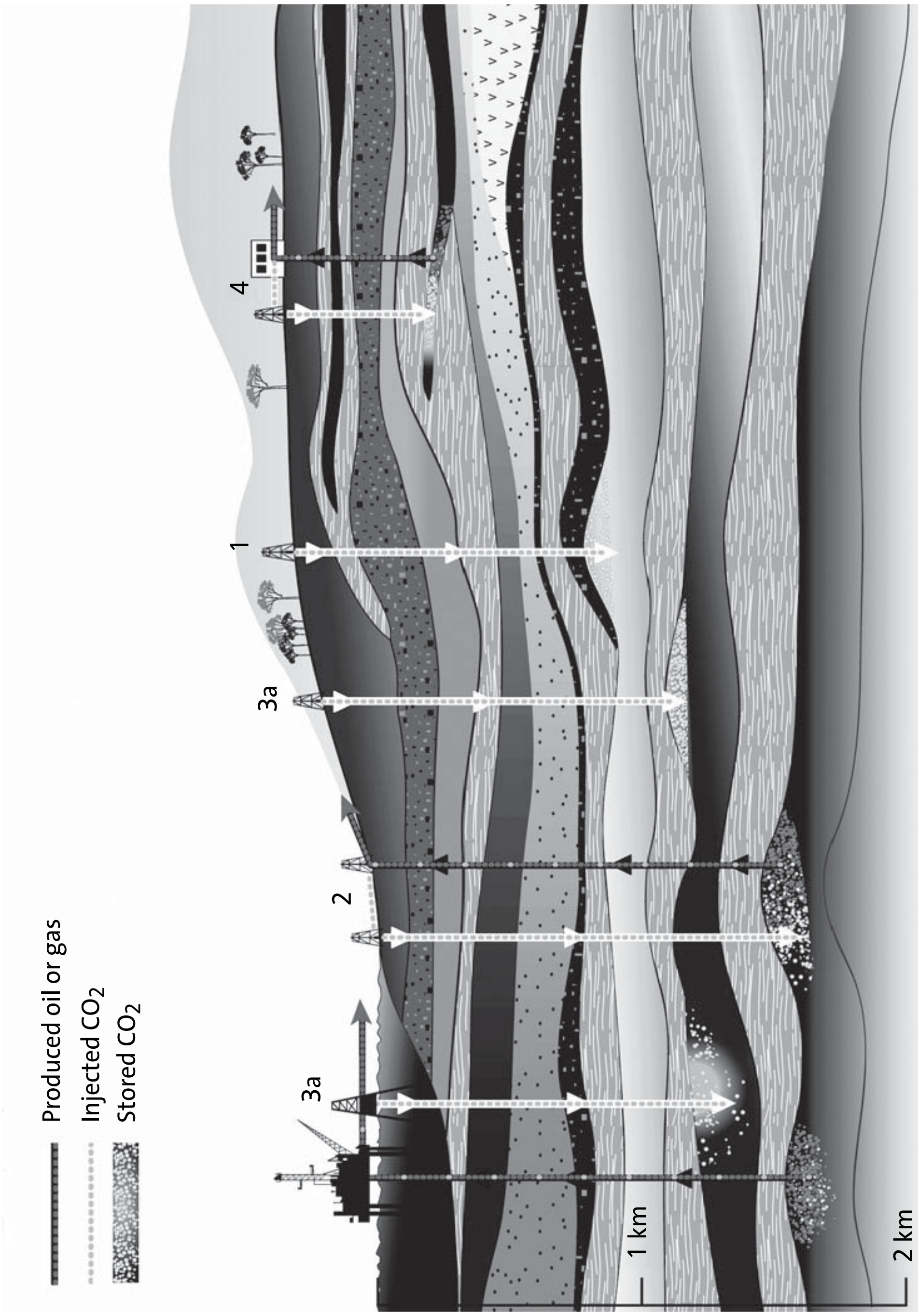


Source: IPCC 2005, p. 208

First of all, there should be caprock (or a series of layers) located above the storage formation that is as CO_2-impermeable as possible (»structural and stratigraphic[6] trapping« in Fig. 7). CO_2 can then be kept in place by adsorption and capillary forces in the rock's fine pores. Also, CO_2 will dissolve in the formation water to a certain extent and finally (on a time scale of several thousand years) convert into solid minerals (IPCC 2005, pp. 208 ff.). CO_2 that is kept in place only by the caprock is potentially mobile and could escape again (e.g. along faults in the caprock), whereas the permanence of storage becomes successively greater in the other mechanisms[7] (Fig. 7). Formations that might be suitable for geological CO_2 storage are mainly (Fig. 8):

6 Based on the sequence of layers.
7 CO_2-saturated water, for instance, has a higher specific weight than pure water, so that it would tend to sink in the reservoir.

FIG. 8 **OPTIONS FOR GEOLOGICAL CO_2 STORAGE**



1 Depleted oil and gas reservoirs
2 Use of CO_2 in enhanced oil and gas recovery (EOR, EGR)
3 Deep saline formations (a: offshore, b: onshore)
4 Use of CO_2 to increase seam yield (enhanced coal bed methane recovery, ECBM)

Source: IPCC 2005, p. 32, pursuant to a specimen in CO2CRC 2005

1. depleted oil and gas reservoirs;
2. not-yet depleted oil or gas reservoirs (injection of CO_2 to increase oil or gas production – enhanced oil recovery, EOR; enhanced gas recovery, EGR);
3. saline formations (sedimentary rock whose pores are filled with highly salty water);
4. unminable coal seams (possibly together with an increase in the seam yield – enhanced coal bed methane recovery, ECBM).

Since it makes sense to use the pore space of reservoirs as efficiently as possible, the injected CO_2 should have a high density. The supercritical state suitable for this is stable at a minimum depth of approx. 800 to 1,000 m (IPCC 2005, pp. 197 f.). It is in this depth range that the most promising storage space is found. At greater depths, rock porosity tends to fall, and development outlays rise significantly due to the drilling technology involved.

Whether CO_2 can be stored safely in geological formations in the long term can be clarified ultimately only by large-scale field trials and their analysis. The options to be considered for storage sites have the following specific characteristics:

DEPLETED OIL AND GAS RESERVOIRS 3.1.1

Oil and gas reservoirs have the merit that their permanent impermeability has been proved across a period of millions of years. Thanks to the exploration and exploitation of the repositories, the structure and composition of the storage and sealing formations are relatively well understood. At least some of the existing infrastructure for the extraction and the transportation of liquids and gases could be usable for the transport and storage of CO_2.

The biggest problem for storage safety is the presence of many old drill holes in oil or gas fields (Ide *et al.* 2006). Finding and, specifically, sealing all drill holes is a costly procedure (FhG-ISI/BGR 2006, p. 105). Furthermore, storage safety could be jeopardized by changes in the caprock (e.g. subsidence) due to oil or gas extraction or to chemical reactions of the CO_2 with the rock (together with water, CO_2 forms carbonic acid that can dissolve certain rocks) (Christensen/Holloway 2004, pp. 8 f.).

In Germany, some natural-gas reservoirs are in their final phase of production, so that potential fields would be available for CO_2 storage (possibly in conjunction with enhanced gas recovery, see below) in the coming years. Oil fields offer only very limited storage volume in Germany, so that they are of less interest (FhG-ISI/BGR 2006, p. 118)[8].

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8 EOR could, however, play a role in the early application and trialling of CCS, e.g. in demonstration projects.

EOR, EGR 3.1.2

The injection of CO_2 into oil repositories with the aim of increasing the yield of oil fields (enhanced oil recovery, EOR), is an established technology. In EOR, CO_2 is injected into an oil field, displacing the oil in the reservoir and lowering its viscosity, which increases the flow to the output wells. Although the original object of EOR was directed more toward recovering as much of the input material CO_2 as possible, the experience gained here can be ported to the permanent storage of CO_2.

One major advantage of this process is that the production of additional oil generates revenue which reduces the costs of storage. The biggest EOR project currently is located in Weyburn/Canada (since 2000). There, the CO_2 produced at a plant in North Dakota/USA making synthetic fuels from lignite is injected via a 320-km-long pipeline into an oil field in order to improve its productivity and, at the same time, store CO_2. Enhanced gas recovery (EGR) to increase the productivity of natural-gas repositories is being trialled only on a small scale at present in some pilot projects.

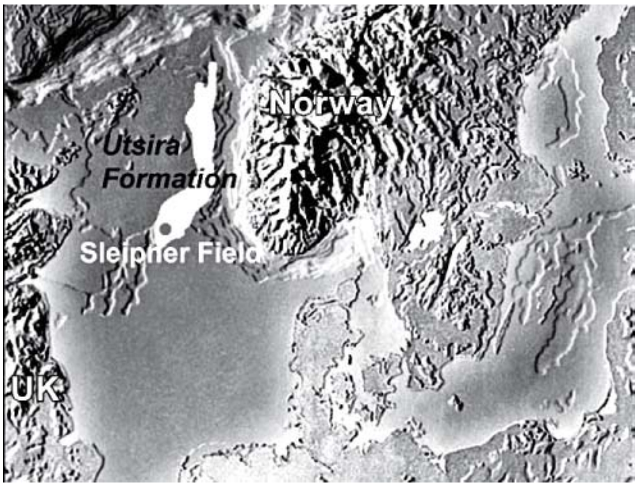
SALINE AQUIFERS 3.1.3

Saline aquifers are highly porous sediments saturated with a strongly salty solution. The pore space can be used to take up CO_2; this displaces some of the formation water. The optimal solutions for CO_2 storage are domed structures which limit the sideways (lateral) migration of the CO_2. But formations without this property, too, can be suitable if they are thick enough. For the suitability as a CO_2-storage site, there must be no risk of CO_2 escaping along crevices, faults zones, etc., in the caprock or of the formation water coming into contact with near-surface groundwater.

In volume terms, saline aquifers offer the biggest potential worldwide for storing CO_2 although their geological and geochemical properties are nowhere nearly so well researched as in the case of oil and gas repositories. This means that, prior to any CO_2 injection, time-consuming and costly investigations will have to be undertaken to ensure the suitability of each formation concerned.

The Sleipner project in the North Sea off Norway is currently the biggest CCS project involving a saline aquifer. There, the CO_2 produced in gas processing (some 1 Mt per year) has been injected into an approx. 800-m-deep formation from an offshore platform since 1996. In Germany, the feasibility of the process is being investigated in a pilot trial near Potsdam (CO_2SINK) (www.co2sink.org).

FIG. 9 **THE SLEIPNER PROJECT**



Source: Chadwick *et al.* 2007

UNMINABLE COAL SEAMS, ECBM 3.1.4

Coal in unminable seams, too, has a pore structure that could be suitable for CO_2 storage. Here, adsorbed methane (»coal bed methane«) is displaced, and this could be extracted and used (enhanced coal bed methane recovery, ECBM). A considerable economic advantage would result if this process were used. Another advantage would be that there are often power plants near coal deposits, so that CO_2 transport routes can be minimized.

One problem with the process is that coal – on contact with CO_2 – tends to swell, so that it becomes more and more difficult to inject CO_2. Strategies to solve this problem include selecting formations with a very high initial permeability, and geological stimulation processes.

There are currently a small number of field trials and pilot projects in place, e.g. in the Upper Silesian Basin in Poland (TNO 2006) and in San Juan/New Mexico (NETL 2007, p. 59).

Due to the location and properties of the coal seams in Germany, ECMB will probably not be an option there in the medium term (FhG-ISI/BGR 2006, p. 102).

OTHER STORAGE OPTIONS 3.2

In addition to the options described above, other possibilities are occasionally discussed for keeping CO_2 away from the atmosphere. What all of them have in common is that – in Germany at least – they are not being seriously considered at present. The reasons for this are, above all (see also UBA 2006a, pp. 77 ff.):

OCEAN STORAGE

Storage in the water columns of the oceans is associated with considerable environmental impact and risks that have hardly been researched so far. Any CO_2 injection into the ocean would lower the pH of the water (the water becomes acidic) and perceptibly change the ocean's chemistry all around the injection point. The permanent effects on organisms and ecosystems are still largely unclear (IPCC 2005, pp. 37 ff.). This being so, the international political debate has (as yet) completely ignored ocean storage. Nevertheless, active research efforts are being made in this area, especially in the US, Japan and Norway (FhG-ISI/BGR 2006, pp. 83 ff.; IEA GHG 2002).

ARTIFICIAL MINERAL CARBONATION

This method involves having CO_2 react with a source rock (usually silicates) to form carbonates, binding it as a result. This imitates a natural process of rock weathering. The challenge is to accelerate this process, which is extremely slow in nature (taking – depending on the mineral – many thousands of years), in such a way that it becomes technically manageable (Herzog 2002).

The large amounts of source rock – 5 t and more per t CO_2 (FhG-ISI/BGR 2006, pp. 90 f.) – that would have to be mined, processed and transported, along with the high energy requirements of the process and the likewise large amounts of carbonates produced that would have to be disposed of – each with its own specific negative environmental impact – severely limit this process in practice (IPCC 2005, pp. 324 ff.).

INDUSTRIAL USE OF THE CO_2

Even if some options exists for industrial use of CO_2 (production of urea, CO_2 as a solvent, etc.) (OECD/IEA 2003), it must be borne in mind that, in many of these use forms, CO_2 is deployed in such a way that it will re-enter the atmosphere after use with a time lag, so that no long-term climate protection is obtained in this way. If only those processes are taken into account in which the CO_2 remains bound in the long term, the theoretical potential of this option – max. 5 % of worldwide CO_2 emissions – is negligible (WD 2006, pp. 15 f.).

STORAGE IN SHUT-DOWN COAL MINES AND SALT DOMES

In Germany, these options are usually ruled out due to safety concerns or competing uses (FhG-ISI/BGR 2006, pp. 92 ff.).

POTENTIALS, RISKS, COSTS III.

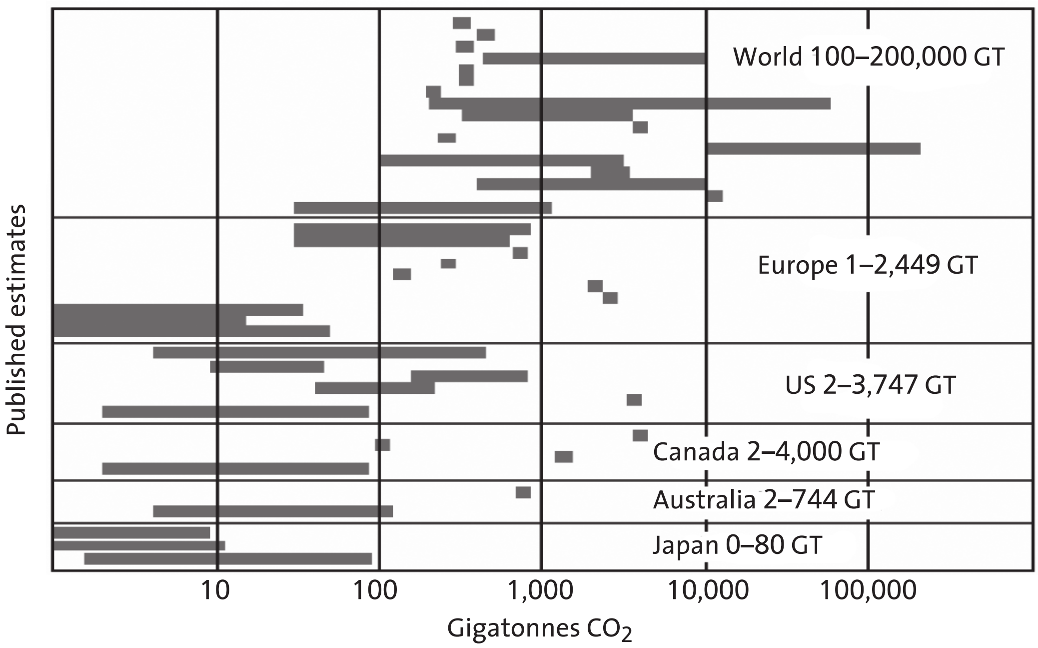
POTENTIALS FOR GEOLOGICAL CO_2 STORAGE 1.

CO_2 capture and storage can only make a perceptible contribution to climate change if sufficient suitable storage capacities are available to actually accommodate the captured CO_2. At present, only relatively sweeping assessments of the potential storage capacities exist for most world regions. Merely a few particularly promising geological formations have been or are now being investigated in detail. The account is geared to the expertise commissioned by the TAB (Ecofys 2007).

ESTIMATED POTENTIALS 1.1

Estimates of global storage potentials show a great bandwidth and are subject to considerable uncertainties. Both the stated range within specific estimates and the difference between the various publications are in the area of a factor of 100 in places (Fig. 10).

FIG. 10 PUBLISHED ESTIMATES OF STORAGE CAPACITY



Source: MIT 2007a, p. 46

For any dependable assessment of the relevance of CCS for climate protection, current estimates of potentials are much too imprecise, therefore (MIT 2007a, p. 46).

The uncertainties differ widely for the various storage options, as Table 1 shows: the capacities of oil and gas fields can be quantified with relative precision (thanks to comprehensive data collection in the course of oil and gas extraction). Aquifers have the largest storage capacities worldwide – also in Germany – although the reliability of the data is particularly low here as well. In the case of coal seams, too, which have the lowest capacity overall, considerable uncertainties exist.

For Germany, the relevant options for storing the captured CO_2 mainly involve exhausted gas repositories and aquifers. To illustrate the order of the stated storage capacities: for Germany, they are roughly 40 to 130 times the annual CO_2 emissions of the German power-plant fleet (350Mt in the reference year 2002) (UBA 2006a, p. 35).

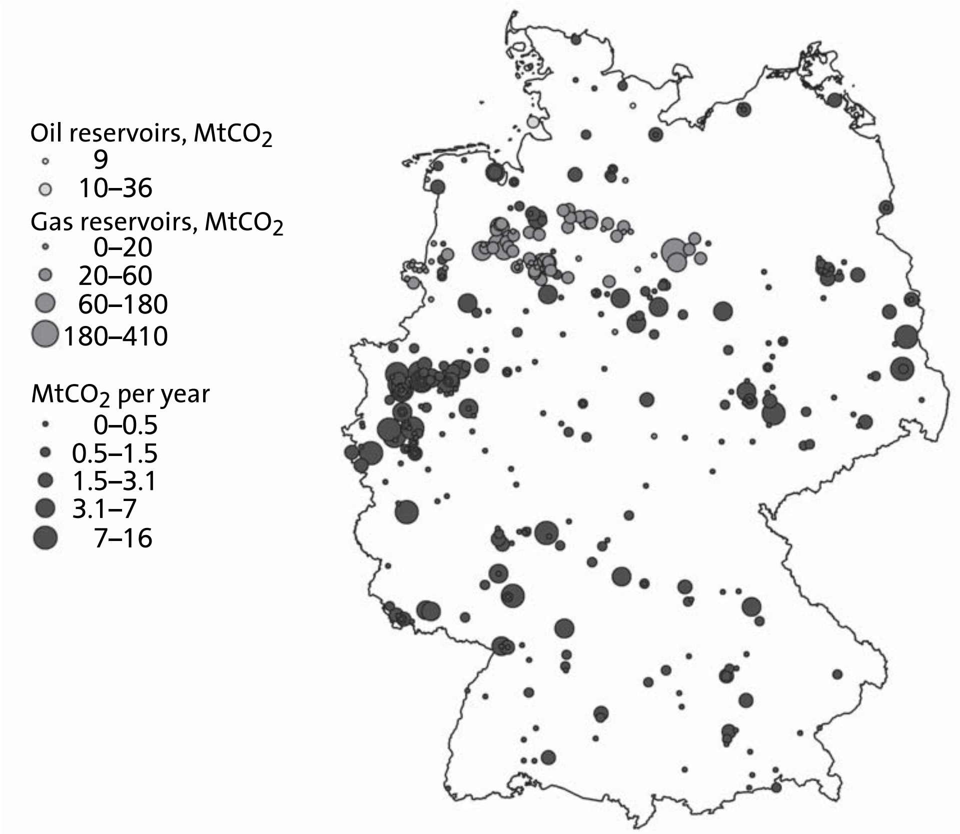
TABLE 1 ESTIMATES OF CO_2-STORAGE CAPACITIES

Storage option	Capacity (in bn t CO_2)		
	Global	Europe	Germany
Depleted gas reservoirs	675–900	31–163	3
Depleted oil reservoirs/EOR		4–65	0.1
Aquifers	1,000–10,000	1–47	12–28
Unminable coal seams/ECBM	3–200	0–10	0.4–1.7
Source	IPCC 2005	Hendriks *et al.* 2004	Christensen *et al.* 2004

Source: Ecofys 2007, p. 12

Most of the possible storage capacities in aquifers are located in northern Germany. They are to be found above all in large sections of the North German Basin and extend to Poland in the east and to England in the northwest. Other potentially suitable aquifers are located in southern Germany's Molasse Basin, in the Upper Rhine Rift, in Munsterlander Bucht, in parts of the Lower Rhine Rift and in the Thuringian Basin (FhG-ISI/BGR 2006, p. 121). In the short to medium term, exhausted gas fields probably offer the most promising option since, in many cases, the existing infrastructure from gas extraction can be recycled, and since the geological properties of the reservoirs are very largely known already. Most of these, too, are located in the north of Germany (Fig. 11).

FIG. 11 LOCATION OF GAS OR OIL REPOSITORIES AND CO_2 SOURCES IN GERMANY



Source: own illustration with data from FhG-ISI/BGR 2006

Since CCS projects can also cross borders, Europe's storage potentials, too, should be examined. Here again, the largest capacities can be found in depleted gas fields and aquifers. Most of the reservoirs lie in the north of Europe (Hendriks *et al.* 2003b).

A huge storage potential in the form of aquifers exists off Norway's coast (e.g. the Utsira Formation: capacity some 350bn t CO_2) (Holloway/Lindeberg 2004) and is also assumed in the British and Danish sections of the North Sea (Christensen/Larsen 2004, p. 13). In the Netherlands and Belgium, there are mainly exhausted gas reservoirs and, possibly, coal repositories as well to be considered.

CONSTRAINTS, COMPETING USAGE RIGHTS 1.2

Whether the potential for CO_2 storage described above is economically tappable and can be used at all depends on a range of geological details, on underlying economic, legal and political conditions, and on social acceptance. It must be expected that the actually usable capacities will turn out to be much lower than those cited in the estimates of the theoretical potential.

GEOLOGICAL CONSTRAINTS

Although it is possible, in the case of aquifers, to calculate what CO_2 amount could be stored in theory from the estimates of the porosity (permeability) of the rock and from the extent and thickness of the formation, individual investigations into specific aquifers are necessary (Hendriks *et al.* 2003a)[9] if we are to determine capacity and suitability for permanent CO_2 storage with more precision. In addition to the density of the caprock – it should be as free as possible from fault zones – and the necessary high porosity of the storage formation, the geochemical properties of storage formation and caprock, too, are of enormous importance, so that undesired reactions of the CO_2 with the in-situ minerals can be ruled out. For such detailed investigations, exploratory wells usually have to be put down, which can be time-consuming and costly.

ECONOMIC CONSTRAINTS

As CO_2 sources (i.e. power plants with CO_2 capture) and storage sites would have to be available in parallel and in a coordinated fashion, temporal or regional constraints exist that make the choice of site and, hence, the tapping of storage potentials more difficult. The storage sites should be located as closely as possible to the sources of the CO_2 emissions, so that transport costs can be contained. Every possible storage structure must be sufficiently large to make developing it worthwhile. In the worst case, for example, there might be great overall potential, but with very many, very small storage structures, so that the site would not really be an option economically.

LEGAL CONSTRAINTS

If the cited potentials are to be tapped, a legal framework must first be created that permits the storage of CO_2 in geological formations at all. Depending on the regulations involved, the available potential may be more or less constrained.

COMPETING USAGE RIGHTS

The formation water of aquifers is not suitable for human use as drinking water or for irrigation due to its high salt content. However, the geological formations predestined for CO_2 storage have properties that make them attractive for other

9 Holloway/Lindeberg (2004) give an example for the Utsira Formation: total pore volume is stated at 600bn cbm. At a depth of > 700 m suitable for CO_2 storage, it is 470bn cbm. If storage in trap formations is demanded, capacity falls to 3.98bn cbm, of which 1.48bn cbm is referred to as »accessible«; this equates to a mere 3‰ or so of total capacity.

use forms as well. These are mainly the interim storage of natural gas as well as deep geothermal energy. Here we have potential conflicts of use.

With the current increase in Germany's natural-gas consumption, the demand for gas-storage facilities, too, is rising in order to offset seasonal fluctuations in demand. This being so, regional conflicts of use might result, e.g. in the catchment area of the planned Baltic Sea pipeline from Russia to Germany.

Aquifers at depths of some 1,000 m and more carry hot water with temperatures of over 100°C that can be considered for energetic use (heat and power) (TAB 2003). To what extent a conflict of use between CCS and geothermal energy must be expected, however, is still unclear at present, since neither the future expansion of geothermal energy use nor the dynamics of CCS can be reliably forecast.

The literature has largely ignored this potential conflict to date. The few available publications arrive at contradictory results. Kühn/Clauser (2006), for instance, discuss possible synergies of geothermal energy production with the mineral trapping of CO_2, while Christensen/Holloway (2004, p. 11) conclude that most of the injected CO_2 by far would re-surface and that the integrity of the drill holes may be at risk due to the aggressive CO_2-water mixture. Some experts are of the opinion that conflicts of use can be diffused by spatial separation. CO_2 would be sequestered in dome-like sediment structures, while geothermal energy would be produced in structural valleys (AUNR 2007). Huenges (2007), on the other hand, points out that, for physical reasons, restricting the use of CCS to domes cannot be ensured.

RESEARCH NEEDS 1.3

There is considerable need for research to underpin the estimates of storage potentials, especially in aquifers (FhG-ISI/BGR 2006, p. 130). To gain more exact data, detailed investigations of individual formations are indispensable. Approaches can be found in some current research projects (e.g. the GESTCO project). These efforts would have to be stepped up significantly, however.

In the area of competing usage rights, there is urgent need for research, and this should be addressed wherever possible before a fait accompli has been created. This also includes the issue of how conflicts of use would have to be resolved (e.g. priority rules).

RISKS, ENVIRONMENTAL IMPACT 2.

Along the entire CCS process chain, there is a possibility of CO_2 escaping. In general, a distinction should be made between local environmental risks and risks for the climate (Table 2). Local risks concern effects on humans, animals and the environment. In low concentrations, CO_2 is harmless; air contains approx. 0.04 %, and it is essential for plants' photosynthesis. In higher concentrations, however, it can have harmful effects (WD 2006, p. 30). Since CO_2 is heavier than air, it can accumulate on the ground, e.g. in sinks, in the event of leakages and may entail an asphyxiation risk for living organisms (upward of a concentration of 10 % by volume).

TABLE 2 TYPIFICATION OF RISKS IN CO_2 STORAGE

Type of risk	Local risk for humans, animals and environment	Global risk for the climate
Spontaneous escape of CO_2 (»accident«)	Short-term, passing, massive impact; life-threatening in worst case	Release of the captured CO_2 amounts
Slow, gradual leakage from storage facility	Chronic and creeping threat to groundwater, flora and fauna in soil; possible danger for humans at point sources	Release of the captured CO_2 amounts

Source: UBA 2006a, p. 58

Other potential local effects of escaping CO_2 are the acidification of drinking-water deposits and negative implications for flora and fauna. Since the risk involved in any sudden escapes of large CO_2 amounts could be life-threatening in the worst case, such a scenario should be ruled out as far as possible. For example, there is much to be said for dispensing with CO_2 storage in earthquake-prone regions (UBA 2006a, p. 58).

In the second risk category, »climate«, it is of less importance whether the leakage is sudden or gradual; the crucial point is the amount of CO_2 released into the atmosphere with an impact on the climate. Even low leakage rates could jeopardize the achievement of future climate targets.

STORAGE SAFETY

In general, the risk posed by the technical systems is assessed as low (pipelines), or as manageable with the usual technical measures and controls (compressor stations, systems for CO_2 capture and injection) (Vendrig *et al.* 2003). Hence, most studies that deal with the risks of CCS technology focus on the implications of CO_2 escaping from geological storage formations.

In an overall assessment of the safety of geological storage formations, the Intergovernmental Panel on Climate Change (IPCC) has issued the following statement: »Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99 % over 100 years and is likely to exceed 99 % over 1,000 years[10].« (IPCC 2005, p. 14).

The actual minimum retention time required for CO_2 in the geological reservoir if CCS is to make a positive contribution to lowering greenhouse gases (GHGs) in the atmosphere is moot. The time spans usually discussed are 1,000 to 10,000 years, i.e. a max. annual leakage rate of 0.1 % or 0.01 % of the injected amount. In Germany, both the Federal Environment Agency (UBA 2006a, p. 68) and the German Advisory Council on Climate Change (WBGU 2006, p. 82) are advocating a retention time of at least 10,000 years. The WBGU also points out that – with a leakage rate of 0.1 % – the max. CO_2 emissions still allowed for achievement of the 2°C target could, in the long term, be already caused *entirely* by emissions from geological storage sites.

As things stand today, the most important processes that could impact the safety and permanence of CO_2 storage are (Christensen/Holloway 2004; Holloway/Lindeberg 2004):

Geochemical processes: reactions of the CO_2-water mix with the caprock or the storage matrix – chiefly the dissolution of carbonates by the carbonic acid – which can weaken the geological formations (all the way to their collapse) and lead to the formation of cracks and, hence, to the opening of leakage pathways.

Pressure-induced processes: the CO_2 must be injected into the formation under a certain over-pressure. This pressure can widen pre-existing smaller cracks in the caprock (so-called »hydrofracturing«, a process that is used in oil/gas technology and for geothermal energy (TAB 2003, pp. 63 ff.)), and may trigger microseismic events that could impair the integrity of the reservoir.

Leakage from existing drill holes: drill holes could open up a direct route back to the earth's surface for the injected CO_2. This is of significance above all in natural-gas/crude-oil repositories and constitutes the biggest leakage risk here. Not all old abandoned drill holes ways are always known in a field.[11] Even if they were sealed according to the state of the art, the materials used (mainly steel

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10 »Very likely« in this respects mean a probability of 90 to 99 %, »likely« of 66 to 90 %.

11 For example, more than 350,000 wells were drilled the Alberta Basin in Canada's west (IPCC 2005, p. 244).

and Portland cement) might be insufficiently CO_2- or acid-resistant (Lempp 2006).

Other open issues: even with careful exploration and responsible selection of storage areas, unidentified migration pathways could exist in the caprock. Also, some of the formation water is displaced by the injected CO_2 and has to move laterally. This lateral dispersion may well affect many square kilometres. The events associated with this have not yet been sufficiently examined and understood by science. There is an acute research need here.

Global statements on the safety of specific storage types only make sense if they are subject to qualifications and will by no means suffice for a concrete siting decision on injecting CO_2. For that, each candidate reservoir would have to be individually investigated to identify its specific features. Hence, further studies and field trials must be urgently conducted in order to assess the risk profiles of geological reservoirs.

MONITORING

The storage safety of geological reservoirs is not just a matter of geophysical and geochemical properties, but also depends crucially on having a sufficient level of knowledge ensured by suitable regulation and continuous monitoring in order to minimize storage risks (Vendrig *et al.* 2003, p. vi.). Monitoring must, on the one hand, verify that no leaks occur in the storage site and, on the other, create a basis for forecasts of the long-term behaviour of the site and its contents.

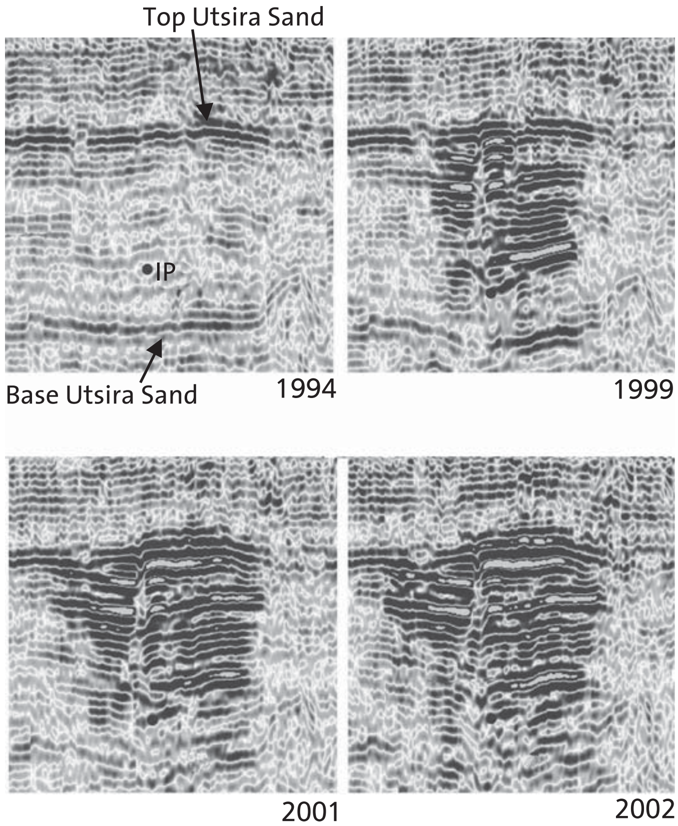
The subject of monitoring is closely linked to liability issues regarding potential leaks, social acceptance of CCS and regulatory issues. If, for instance, CCS is to be recognized as emission reduction under the Kyoto Protocol, a dependable monitoring system must be put in place that can be used to produce a balance sheet, both quantitatively and verifiably, on the whereabouts of the stored CO_2 amounts.

Various technologies from oil and gas production can be adapted and used to monitor underground CO_2 (Pearce *et al.* 2005). The widely used and comparatively reliable procedures mainly include seismic methods (Fig. 12), but acoustic (e.g. sonar) and electric measurements, too, are suitable in principle.

These measuring methods, when combined with numeric simulations, are to provide information on whether storage formation and CO_2 migration are behaving as expected. Less experience is available on the monitoring of leakages into the atmosphere. The chief options here are infrared measurements (possibly also as remote monitoring in conjunction with aircraft or satellites) and, inter alia, groundwater and soil chemical analyses, but also the observation of ecosystems (IPCC 2005, pp. 234 ff.).

Despite its outstanding importance, the subject of monitoring is under-represented in the literature on CO_2 capture and storage. Clarification is required, e.g., on how long monitoring of the CO_2-storage site is to be done – and by whom. Also needed is a definition (and possibly coordination at international level) of the monitoring procedures to be demanded or accepted within the scope of approval procedures.

FIG. 12 EXAMPLE OF MONITORING: SLEIPNER PROJECT



IP: point of CO_2 injection

Vertical cross-sections through the expanding CO_2 plume (dark spots): before the injection in 1994, and in 1999, 2001 and 2002. The images were generated using seismic measurements. The height of the CO_2 plume is about 250 m, the lateral expansion approx. 2 km (in 2002).

Source: www.bgs.ac.uk/science/CO2/Sleipner_figs_03.html, reproduced with permission of the British Geological Survey© NERC; all rights reserved

The periods for geological storage go well beyond the lifecycle of most institutions, so that it is difficult to guarantee monitoring and liability for emissions across such a period. It has been proposed that the various governments assume the monitoring after the end of the active phase of a project, provided that all statutory requirements were met during the operating phase (IPCC 2005, p. 241). Another suggestion involves ending the monitoring activity as soon as evidence is submitted that the CO_2 is no longer expanding (Benson *et al.* 2004; Chow *et al.* 2003), or even discontinuing it as a rule once the injection wells have been sealed (50 to 100 years after the start of a project) (Pearce *et al.* 2005).

When responsibility is transferred to states, the question remains of whether monitoring or its control can be secured in the long term and who is to assume the costs. Cost assumption, in particular, must be discussed against the background of inter-generational fairness.

CONTAMINATED CO_2

Another aspect of environmental impact that is often addressed only superficially as an issue is that of possible contaminants in the CO_2 to be stored (IPCC 2005, pp. 141 f.). The gas captured from power-plant and industrial processes may also contain – besides CO_2 – nitrogen oxides (NO_x), sulphur compounds (SO_x, H_2S), hydrogen (H_2), carbon monoxide (CO), methane (CH_4) and natural-air components. Despite their low percentage shares, such residues would be stored in substantial amounts due to the large storage volumes involved.

There is a need for research both as regards the interaction of contaminated CO_2 with the technical infrastructure (material problems, corrosion, etc.) and as regards storage problems (impairment of drill-hole seals, implications for storage capacity, injection rate, etc.). In addition, it should be ensured that no unplanned escapes lead to harmful effects on ecosystems (UBA 2006a, p. 59).

TRIGGERING OF EARTHQUAKES

One question often asked, above all by the general public, is whether underground injection of CO_2 can cause earthquakes. Earthquakes are known to occur in connection with gas/oil production, coal mining and geothermal-energy projects (Bojanowski 2007; SED 2006; Töneböhn 2007). In the mid-1970s, for example, several very strong quakes (magnitude 7 on the Richter scale) occurred in Uzbekistan for which natural-gas extraction was blamed. Germany and neighbouring countries, too, have recently seen earthquakes in gas-production regions, e.g., a tremor with magnitude 4.5 in Rotenburg (Lüneburg Heath) in 2004 and two minor quakes (magnitude 3 and 2.4 resp.) near Groningen (Netherlands) in 2003 and 2006. As these regions had not previously been seismically conspicuous, the conclusion is obvious that gas production must be made responsible for these tremors, even if natural causes cannot be entirely ruled out scientifically.

Underground CO_2 injection on an industrial scale is associated with major shifts in volumes and leads to changes in pressure in geological formations that are comparable with the processes known from gas/oil extraction. However, the (limited) experience available of injecting fluids in deep rock formations (e.g. EOR, the dumping of waste water and hazardous substances) suggests that the seismic risk is not very pronounced. Careful selection of storage sites and rules that set strict upper limits for max. permissible pressure or permitted volumes when injecting CO_2 could contain these risks (IPCC 2005, pp. 249 f.).

The current state of our knowledge is nowhere near sufficient to justify, e.g., quantitative statements on CCS-induced earthquake probabilities. Acute research needs exist here.

OTHER ENVIRONMENTAL IMPACT

When considering the environmental impact of CCS, account must also be taken of greater inputs of fuels and other materials as well as the use of transport infrastructures (e.g. the use and construction of pipelines) and their ecological effects. Initial carbon-footprint analyses of the entire process chain have appeared recently (Pehnt/Henkel 2007; WI/DLR/ZSW/PIK 2007), although further research need exists.

COSTS, COMPETITIVENESS 3.

The costs of CO_2 capture and storage are composed of the outlays for the various process steps (capture, gas conditioning, transport and storage). In addition, there is power plants' loss of efficiency caused by CO_2 capture and the associated higher consumption of primary-energy sources. For an assessment of the competitiveness of CCS with other power-generation options, it is mainly the power costs and CO_2-avoidance costs that are relevant. An abundance of literature deals with the costs of CCS. A detailed overview of the various cost estimates is offered by the IPCC (2005), for example.

CO_2 CAPTURE 3.1

There is broad-based consensus that the outlays for CO_2 capture are the dominant cost factor. Since most capture techniques have not yet been trialled on a commercial scale, these cost estimates are based on studies of hypothetical plants (IPCC 2005, p. 149), so that they are marked by some uncertainties. Hendriks *et al.* (2004, p. 32) quantify these uncertainties at ±30 %.

Table 3 shows typical calculations for power-plant types with pre- or post-combustion technology[12]. The power costs for IGCC plants and gas-based CCGT/post-combustion stations rise by about a third due to CO_2 capture, the increase for coal-fired power plants with post-combustion capture being approx. 50 %. The results are in relatively good agreement with those of two current studies (Table 4).

Only for the post-combustion capture at coal-fired power stations does MIT (2007a) state a much higher value of 60 to 75 %.[13]

TABLE 3 COSTS OF CO_2 CAPTURE FOR POWER PLANTS

Type of capture technology	Pre-combustion	Post-combustion	
Type of plant	Coal (IGCC)	Gas (CCGT)	Coal (PC)
Without capture			
Plant efficiency (%)	47	58	42
Power costs (Euroct/kWh)	4.8	3.1	4.0
With capture			
Plant efficiency (%)	42.2	52	33.7
Loss of plant efficiency (percentage points)	4.8	6.0	8.3
Power costs (Euroct/kWh)	6.4	4.1	6.0
Extra costs for capture (Euroct/kWh)	1.6	1.0	2.0
Power cost increase (%)	33.3	32.3	50.0
CO_2 avoided (%)	88	85	85
Costs (Euro/Mg CO_2)	26	37	29

IGCC: integrated gasification combined cycle; CCGT: combined-cycle gas turbine; PC: pulverized coal

Source: Excerpt from Hendriks *et al.* 2004, p. 5

The CO_2-capture costs obtained (relative to the amount of CO_2 avoided) are between Euro 26/t and 37/t (compared with a same-type power plant without capture). The stated values are in the mid-range of relevant publications (Audus 2006; IPCC 2005; OECD/IEA 2004a; WI/DLR/ZSW/PIK 2007; Williams 2002).

12 The quoted comparative studies do not consider oxyfuel power plants.

13 Based on a comparative quantitative analysis of seven power-plant design and power-station cost studies.

TABLE 4 COSTS OF CAPTURE FOR POWER PLANTS

Type of capture technology	Pre-combustion	Post-combustion	
Type of plant	Coal (IGCC)	Gas (CCGT)	Coal (PC)
Publication	*Power cost increase (%)*		
Hendriks *et al.* 2004	33.3	32.3	50.0
Strömberg 2006	–	35	46
MIT 2007a	30	–	60–75

Source: own compilation

All of the data refer to power stations to be newly built. The costs of retrofitting existing power plants with CO_2-capture systems have hardly been examined so far. The few studies available indicate that costs are very case-specific, though they tend to be much higher than for new-builds. There is still substantial need for research here (IPCC 2005, p. 170).

The costs of capturing CO_2 from industrial processes are of a similar order as for power plants. Exceptions are those processes in which CO_2 is generated in a nearly pure form anyhow (e.g. ammonia and hydrogen production). There, the costs of CO_2 capture are many times lower (Table 5).

TABLE 5 COSTS OF CO_2 CAPTURE IN INDUSTRIAL PROCESSES

Plant	Euro/t CO_2
Cement	28
Iron and steel	29
Ammonia (flue gas)	36
Ammonia (pure CO_2)	3
Refinery	29–42
Hydrogen (flue gas)	36
Hydrogen (pure CO_2)	3
Petrochemical	32–36

Source: Hendriks *et al.* 2004, p. 5

New and improved CO_2-capture technologies in conjunction with advanced power-plant or process design promise lower costs in future. Assumptions regarding technical advances in various CO_2-capture techniques are generally based on empirical values from similar technologies (e.g. desulphurization plants). A study on learning effects for sulphur dioxide (SO_2) and nitrogen oxides (NO_x) in the US produced a capital-cost reduction of 12 % per doubling of the world-wide installed capacity (Rubin *et al.* 2004). Due to their technical similarity, comparable economies of scale are sometimes assumed for CO_2 capture.

It is undisputed, however, that learning curves cannot be ported without qualification to other technologies, and that cost estimates for technologies in an early development stage are often unreliable and too optimistic. Experience has shown that costs usually rise during the development phase and do not fall until after implementation of one or more commercial plants. This being so, cost statements for the various CO_2-capture techniques should be viewed in the context of their current development phase (IPCC 2005, p. 163).

CO_2 TRANSPORT 3.2

The most frequent and usually also the most cost-efficient form of transporting CO_2 is by pipeline. Where distances are very long, shipping may be economically feasible (IPCC 2005, p. 344).[14]

PIPELINE TRANSPORT 3.2.1

The most important cost elements for pipelines are the costs of material, construction, operation and maintenance as well as energy costs for compression (Hendriks *et al.* 2003b). The costs depend on the quantity to be transported and on transport distances. For a typical transport case (distance 250 km, 5 $MtCO_2$ per year, simple terrain), costs of about US$ 2/t CO_2 (2002) are cited. The bandwidth ranges from US$ 1 to 8/t (2002) (IPCC 2005, p. 345; VGB 2004, pp. 100 ff.).

Depending on geographic features, these may vary greatly: crossings (e.g. roads, waterways) can boost costs by 40 %, mountainous terrain by 80 %, urban spaces by as much as a factor of 10 (FhG-ISI/BGR 2006, p. 75). Offshore pipelines are some 40 to 70 % more expensive than comparable onshore pipelines (IPCC 2005, p. 344).

It must also be borne in mind that the estimated transport costs usually refer to a complete infrastructure, incl the associated economies of scale. In practice, however, the transport infrastructure is built up successively, so that, initially, a

14 The IEA has announced that it will make available in early 2008 a software tool for calculating transport costs. Further details at www.co2captureandstorage.info/co2cost calculator/co2transmission.htm.

lower rate of capacity utilization and higher costs must be expected (Linßen *et al.* 2006, p. 56).

Since pipeline construction can be considered to be a mature technology, future cost cuts from technological progress can only be expected on a small scale (IPCC 2005, p. 344).

As regards the creation of a transport infrastructure, the advantages and disadvantages of constructing project-specific pipelines must be set against those of creating a CO_2 pipeline network. If CCS is implemented on a large scale, the necessary CO_2 transport infrastructure will probably consist of an amalgamation of several coordinated networks (VGB 2004, pp. 104 f.). However, the creation of any notable transport infrastructure can only be expected if the political signals are unequivocal and if long-term planning certainty is in place (Hendriks *et al.* 2003b, p. 23).

TRANSPORT BY SHIP 3.2.2

Cost estimates for transport by ship have been the subject of much fewer investigations, and these also diverge strongly in places. The reason for this is that no shipping system on the scale required for CO_2 capture and storage exists today, so that assumptions must be made that may lead to wider deviation in the results.

The shipping costs are made up of different elements, e.g., costs of the ship, the loading and unloading infrastructure, intermediate storage, harbour fees, energy costs for cooling/liquefaction and personnel expenses.

The costs of the entire processing and transport chain (incl compression and cooling), are put by the IPCC (2005), for example, at around US$ 8/t CO_2, assuming a transport distance of 200 to 300 km.

In transporting CO_2 across very long distances (upward of approx. 1,000 km), shipping may be the lower-cost option compared with pipelines. What is more, ships can be deployed much more flexibly than pipelines.

CO_2 STORAGE 3.3

Drilling, infrastructure and operating costs are the main cost components in CO_2 storage. As storage costs depend very much on the given features (depth, reservoir thickness, permeability, existing infrastructure, etc.) of each individual reservoir, the cost estimates have a relatively large bandwidth (between US$ 0.2 and 30.2/t CO_2 for aquifers and US$ 0.5 and 12.2/t CO_2 for depleted oil and gas fields) (IPCC 2005, pp. 259 f.). In general, offshore storage is more expensive than onshore.

Table 6 gives an overview of the costs estimated by Hendriks *et al.* (2004) as a function of storage-site depth and reservoir type. Storage in aquifers is shown to be slightly more expensive than storage in empty natural-gas or oil fields. Storage costs rise with growing storage depth. The number of drillings required, too, is an important cost factor. This depends, inter alia, on the reservoir's capacitance and other reservoir properties (e.g. the permeability of the rock).

TABLE 6 CO_2-STORAGE COSTS AS FUNCTION OF STORAGE DEPTH

	Storage costs (Euro/t CO_2) at a depth of		
	1,000 m	2,000 m	3,000 m
Aquifer onshore)	1.8	2.7	5.9
Aquifer offshore	4.5	7.3	11.4
Natural gas field onshore	1.1	1.6	3.6
Natural gas field offshore	3.6	5.7	7.7
Empty oil field onshore	1.1	1.6	3.6
Empty oil field offshore	3.6	5.7	7.7

Source: Excerpt from Hendriks *et al.* 2004, p. 13

In the case of enhanced oil recovery (EOR), the revenues from increased oil production may go some way toward offsetting the costs of CO_2 storage or even exceed them. The cost estimates here depend on a whole host of parameters, like the productivity and depth of the reservoir, the existing infrastructure and the effectiveness of CO_2 injection, and can vary significantly with the assumptions made on existing oil prices[15] (Hendriks *et al.* 2004, p. 12; IPCC 2005, p. 262). This being so, various publications may reveal considerable differences: while the estimates of Hendriks *et al.* (2004) range from Euro -10 to 10/t CO_2, for instance, the IPCC (2005) cites a bandwidth of US$ -92 to 66.7/t.

As enhanced coal bed methane recovery (ECBM) and enhanced gas recovery (EGR) are still not within sight of any commercial availability, the cost estimates are marked by huge uncertainties. Among the parameters influencing the costs we find, inter alia, the gas price and the number and depth of the wells, and the effectiveness of storage or methane extraction. The spectrum of existing cost estimates ranges from US$ -26.4 to 31.5/t CO_2 (IPCC 2005, p. 263).

15 Most estimates are based on rather low oil prices of US$ 15 to US$ 20/barrel. For higher oil prices, no differentiated calculations are available (IPCC 2005, p. 262) as yet.

At present, there is an urgent need to update the cost estimates for CO_2 storage. The reason for this is that (due to current developments in the oil and gas industry) drilling costs have more than doubled in just a few years (Huenges 2007). The literature has so far taken no account of these cost increases.

COSTS OF MONITORING, LIABILITY, REMEDIATION 3.4

Hardly any studies exist at the moment dealing with the costs of a long-term monitoring of CO_2-storage sites. These costs mainly depend on the reservoir's given properties, the monitoring technologies employed and the period across which monitoring takes place. Depending on the scope of the monitoring strategy, Benson *et al.* (2005) calculate costs of US$ 0.05 to 0.085/t CO_2 (for the entire duration of monitoring, at a discounting rate of 10 %) or US$ 0.16 to 0.30/t CO_2 (without discounting). This assumes that monitoring will take place during the 30-year injection phase and then be continued for 20 years after the reservoir is closed in the case of EOR, and for 50 years in the case of storage in aquifers.

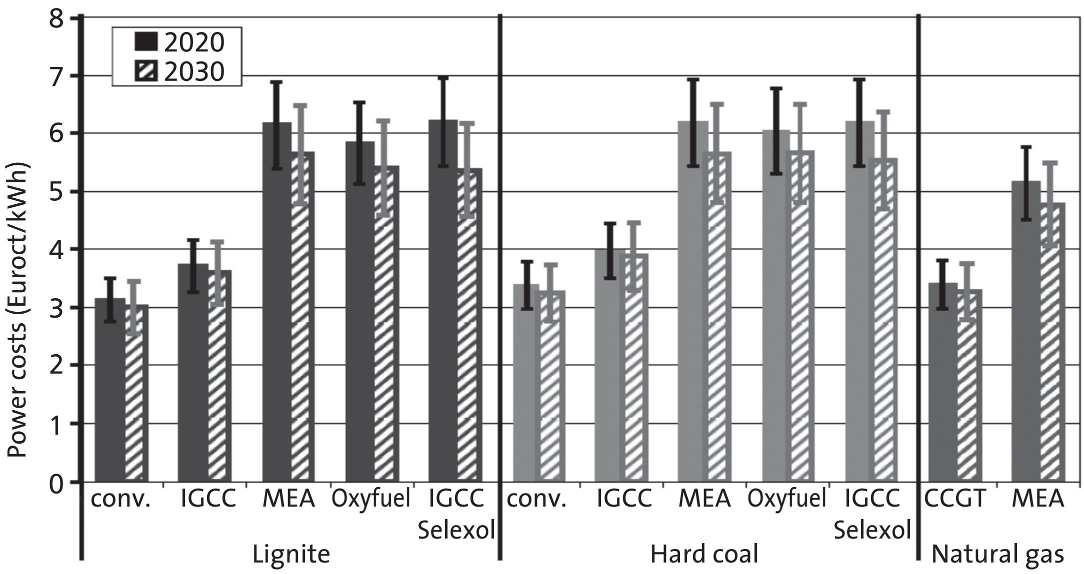
So far, the literature has paid no heed to costs that may arise in the event of leakages for repairs and remediation, or to the costs of long-term liability (IPCC 2005, p. 263). Even if these cost components are likely to account for only a rather small share in the total costs of storing 1 t of CO_2, they should not be neglected due to the large amounts of CO_2 and the long periods of time involved, and should flow into a long-term economic analysis (UBA 2006a, p. 49).

TOTAL COSTS AND COMPETITIVENESS 3.5

After a look at the costs for the various process steps in CCS, what follows will illustrate the total costs of the CCS option, taking account of the entire process chain. The discussion will address both the power costs and CO_2-avoidance costs.

Figure 13 compares the power costs of the three process variants for CO_2 capture: »post-combustion« (MEA), »oxyfuel« and »pre-combustion« (Selexol) with a conventional steam power plant or a combined-cycle plant (IGCC or CCGT). The assumptions were: new power stations to be built in the years 2020 and 2030 resp., pipeline transport over 200 km and storage in an aquifer 1,000 m deep (Linßen *et al.* 2006, p. 51).

FIG. 13 POWER COSTS OF VARIOUS PLANT TYPES WITH AND WITHOUT CCS



Conv.: conventional reference power plant; IGCC: gas and steam power plant with integrated coal gasification; MEA: monoethanolamine; oxyfuel: combustion in pure oxygen; Selexol: physical CO_2-capture process; CCGT: gas and steam power plant

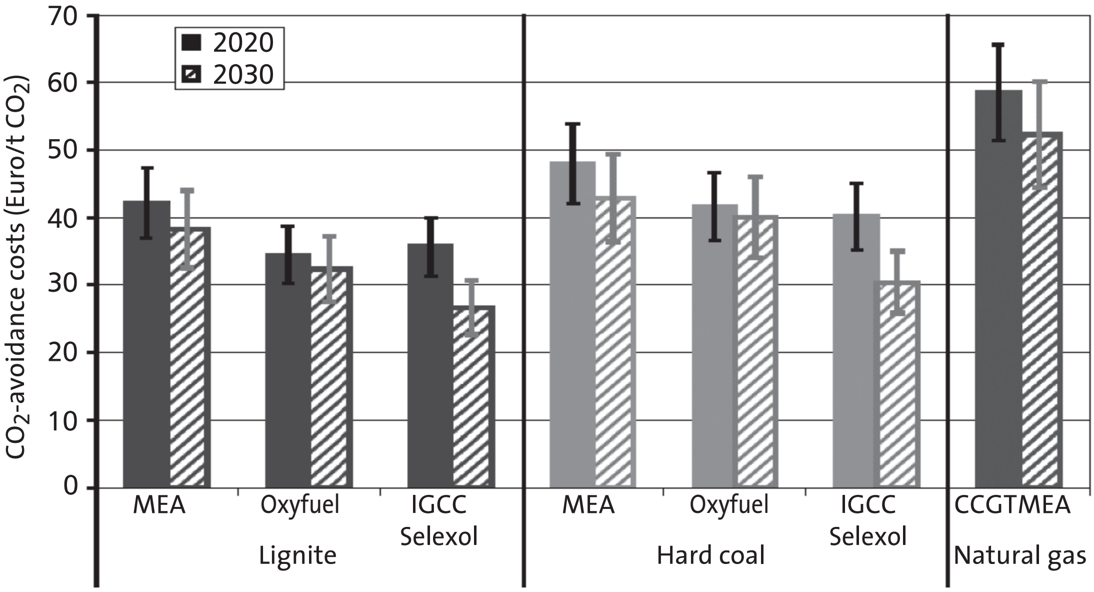
Source: Linßen *et al.* 2006, p. 51

For the coal-fired power-plant variants with CCS, we obtain a virtual doubling of the power costs and for natural-gas combined-cycle stations a 50 % increase. From these results no clear fuel-specific preference from among the power-plant techniques can be inferred for a particular technique (i.e. oxyfuel v pre-combustion, say) (Linßen *et al.* 2006, p. 51).

The calculation of the power costs for the different plant variants is based on a range of assumptions regarding the state of technological development in the target years 2020 and 2030 resp. (e.g. the electric efficiency of the power stations, the degree of CO_2 capture), on cost assumptions (e.g. investments, operating costs) and on further parameters, e.g. interest rates, number of hours under full load and, not least, future developments in fuel prices (coal, gas). These assumptions are associated with considerable uncertainties in places, so that a relatively large bandwidth for power costs emerges.

Figure 14 shows the resulting CO_2-avoidance costs. For coal-fired power plants – assuming market launch around 2020 – these amount to around Euro 35 up to just under Euro 50/t CO_2. For gas-based power stations, they are much higher. WI/DLR/ZSW/PIK (2007, pp. 208 ff.) arrive at comparable results.

FIG. 14 **CO_2-AVOIDANCE COSTS OF POWER PLANTS WITH CCS**



IGCC: gas and steam power plant integrated coal gasification; MEA: monoethanolamine; oxyfuel: combustion in pure oxygen; Selexol: physical CO_2-capture process; CCGT: gas and steam power plant

Source: Linßen *et al.* (2006, p. 53)

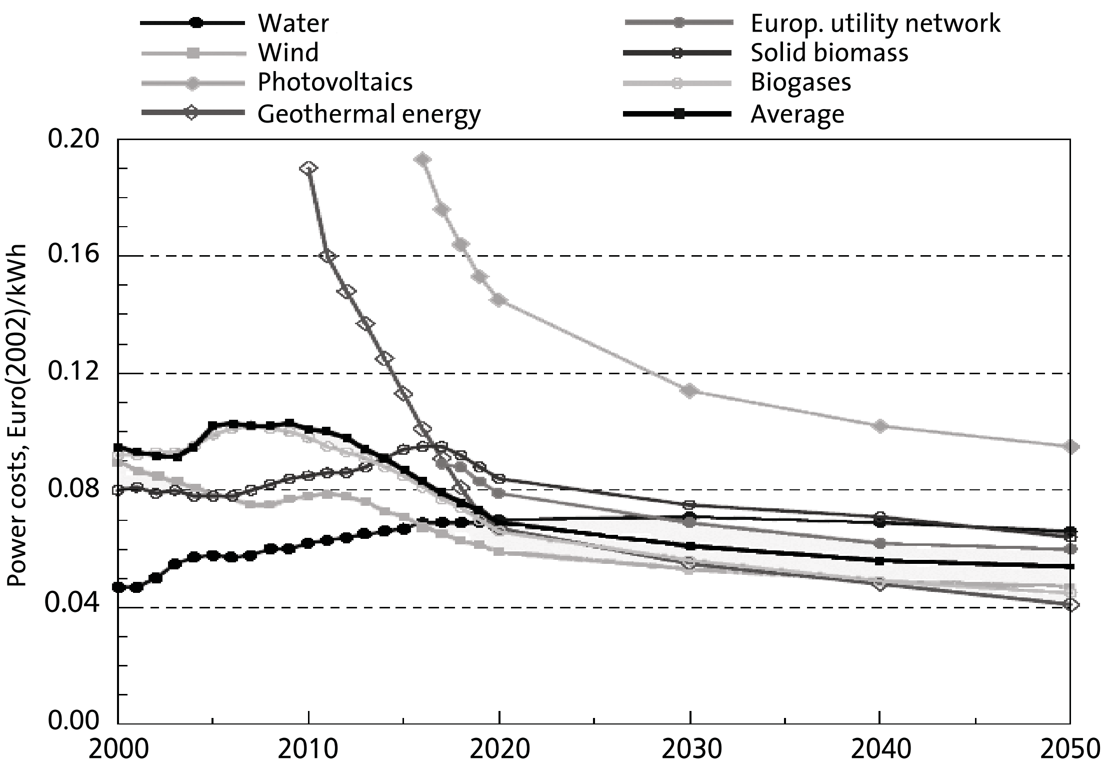
Thanks to learning effects, the avoidance costs could sink to or fall below Euro 30/t CO_2 for some coal-fired variants in 2030. In the CO_2-avoidance costs, the question of a reference power station for a comparison is crucial. If, for instance, a coal-based power plant with CCS is compared with a gas combined-cycle station, much lower CO_2 emissions are avoided, resulting in considerably higher – by up to a factor of 3 – CO_2-avoidance costs (WI/DLR/ZSW/PIK 2007, p. 207). For this reason, the established CO_2-avoidance costs cannot be used as a basis for comparing other CO_2-reduction measures either (e.g. in the building sector or in traffic). This would require considering the overall energy-management situation within the scope of energy-system models (Linßen *et al.* 2006).

COMPETITIVENESS

CCS technology will only be used on the electricity market if it can compete with other generation options. This presupposes that climate-sparing power generation is economically rewarded, or in other words: that the price of emitted CO_2, as formed, e.g., on the European market for CO_2 emission certificates (EU Emission Allowances (EUA)), must be set at least so high that CCS power plants can compete with fossil-fired power stations without CCS. In light of the above CO_2-avoidance costs for CCS, this would be the case at a price of some Euro 30 to 40/EUA.[16] Occasionally, lower amounts (e.g. Euro 15) are considered possible as well (Strömberg 2005).

Under these conditions, a comparison of the power costs for CCS plants with other low-CO_2, above all renewable, production options is interesting. Figure 15 shows cost developments in technologies for renewable-power generation, as indicated by the »Lead Scenario 2006« for new plants to be built (for details, see Nitsch 2007).

FIG. 15 FUTURE COST DEVELOPMENT OF RENEWABLE-POWER GENERATION



Source: Nitsch 2007, p. 47

According to this, most of the renewable technologies considered could, by 2020, have reached a similar cost level as established for CCS power plants (in a range of Euro 0.05 to 0.07/kWh). (For hydropower and wind power, this is already the case at good locations). Under certain scenario assumptions (inter alia, ongoing expansion dynamics for renewables), a competitive edge is noted for renewable technologies in the period after 2020 which will become even greater in the course of time (WI/DLR/ZSW/PIK 2007, p. 212).

16 On the subject of allocations of certificates and incentive effects, see chapter VI.4.2.

However, pure cost comparisons are able to map only part of the competitiveness of CCS, which also depends on other factors, like technical dependability, security of supply, the value of electricity (availability, secured performance), network-integration aspects and the supply potential of the various generation technologies (WI/DLR/ZSW/PIK 2007, pp. 223 ff.).

Although such scenario-based, long-term projections should not be over-interpreted in their forecasting power, it appears undeniable that CCS will have no unique selling point, and will have to hold its own in concert with other technologies for low-CO_2 power generation.

INTEGRATION OF CCS INTO THE ENERGY SYSTEM IV.

Large-scale power plants and the energy infrastructure are associated with high investment costs and long re-investment cycles, so that, on the one hand, significant changes in the power-plant portfolio are only possible in certain time windows, while, on the other, investment decisions in favour of certain technologies have a binding effect across relatively long periods (40 years and more). Should CO_2 capture and storage be considered as a suitable climate-protection option, its launch must go hand in hand with the re-investment cycles in the power-plant sector.

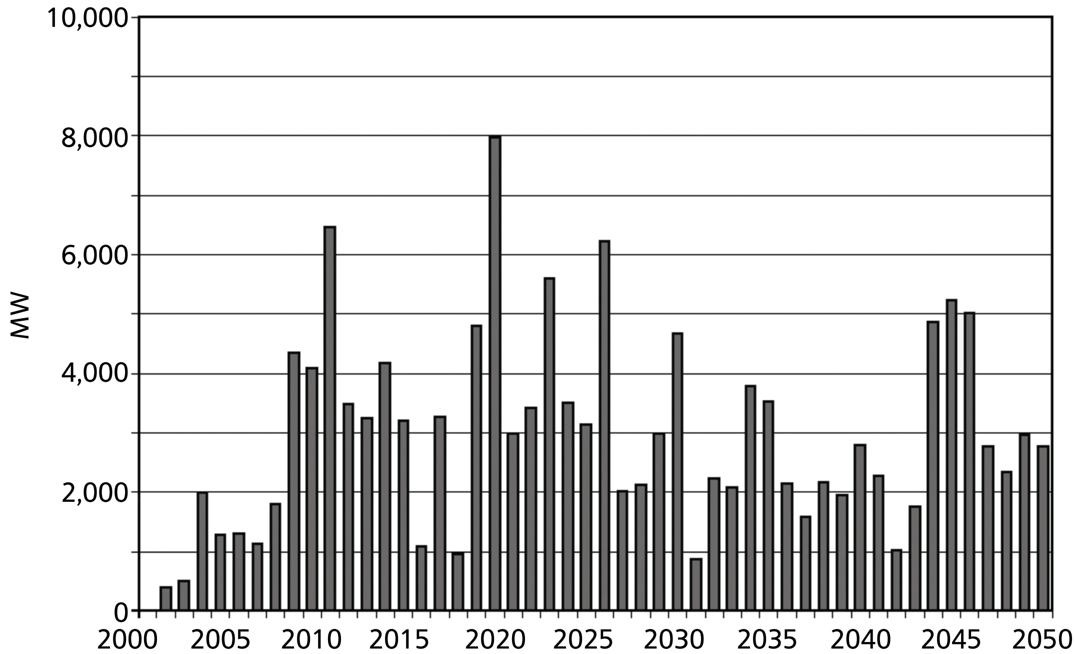
NEED FOR POWER-PLANT RENEWALS 1.

In the next two to three decades, Germany will have considerable renewal needs owing to the age structure of its power plants. Most of the power-station units now in operation are long in the tooth: in 2010, over 40 % of the capacity installed in conventional thermal power plants will have been connected to the grid for 35 years or more. In addition, if the phase-out decision is implemented as scheduled, more than 21,000 MW of installed nuclear-power-station capacity will be taken off the grid completely by the mid-2020s. Hence, a power-plant capacity of least 50,000 MW will have to be replaced by 2030. If modernization is comprehensive, this capacity could even rise to nearly 80,000 MW (DIW 2003).

The projected annual power-plant capacity needs for new-builds in Figure 16 shows that higher needs must be expected especially in the period up to 2030 (Linßen *et al.* 2006). According to the UBA's power-plant database, 45 gas- and coal-fired power-station units are currently planned and due to be commissioned between 2006 and 2015; in total, a capacity of over 30,000 MW (UBA 2006b, pp. 6 ff.).

However, viewed from an energy-management angle, there is no automatism in having to replace shut-down large-scale power stations with other large power plants. The construction of smaller, decentralized power stations located in the proximity of consumers offers a range of advantages: thanks to the greater flexibility they offer, better coordination of power generation and fluctuating demand is possible. Power losses could be decreased thanks to shorter transmission routes. The demand for primary-energy carriers could be diversified and biogenic energy sources more easily integrated, for example. Another important argument for more decentralization is the possibility of making sensible use of the heat produced in power generation (combined heat and power generation, CHP). Another possible strategic element is a significant limiting of the need for new power-plant capacity by redoubling our efforts on behalf of efficient energy use and energy savings.

FIG. 16 ANNUAL NEED FOR NEW POWER-PLANT CAPACITY IN GERMANY



Source: Linßen *et al.* 2006, p. 43

What contribution CCS technology can make to CO_2 reductions against this background crucially depends on the answers to the following questions:

› When will CCS actually be available?
› Is the retrofitting of existing power plants with CCS technology doable?
› Is the concept viable to prepare for retrofitting new power stations being built now (i.e. making them »capture-ready«)?

TIMEFRAME FOR THE AVAILABILITY OF CCS 2.

Various papers on research strategy, as well as roadmaps, address the time horizon by which CCS technology might be available. Most of these publications are agreed in citing the target year 2020 as the date for commercial availability on a power-plant scale, although it is not always clear what exactly is to be achieved by that year. A relatively high degree of detail is offered by both the German

COORETEC programme and by the CCS plan of the American Department of Energy (DoE):

- The COORETEC programme announces the goal of making »the future-capable power plant commercially available« by 2020. The technical sub-targets are relatively detailed. These include, inter alia, lowering the costs of CO_2 capture and storage from today's Euro 50 to 70/t CO_2 to less than Euro 20, as well as reducing the efficiency losses due to CCS from today's 9 to 13 percentage points to 6 to 11 percentage points (BMWI 2007, p. 4). Hence, the technology element that determines the timeframe for the commercial-scale deployment of the CCS technology chain is geological storage. Existing issues are to be clarified by 2010 using pilot projects, so that, by 2020, more than 5 % of the emissions from German power plants are to be »storable« (by 2025, this share may grow to more than 20 %) (BMWA 2003, pp. 79 ff.).
- The roadmap of America's DoE, too, fleshes out the general target »to develop, by 2012, fossil fuel conversion systems that offer 90 percent CO_2 capture with 99 percent storage permanence at less than a 10 percent increase in the cost of energy services« with detailed information (DoE 2007, p. 9). Hence, results from pilot plants for CO_2 capture and storage, incl monitoring and verification technologies, are to be available by 2012 which, taken together, would meet the above requirements. In a next step, system integration and upscaling of these technologies are to be stepped up, so that large plants can go on stream around the year 2020.
- The »European Technology Platform for Zero Emission Fossil Fuel Power Plants« goes even further, its lead vision statement being »to enable European fossil fuel power plants to have zero CO_2 emissions by 2020« (ETP ZEP 2006c, p. 4). The label »zero emission« is harshly criticized in some quarters, however, since it is felt to be misleading.

Specialist circles consider the year 2020, as target date for the marketability of CCS, to be very ambitious. The participants in the expert workshop mounted by the TAB, too, were agreed on this. So far, there has been no demonstration project that covers the entire CCS chain. Although an ambitious time schedule can help accelerate the development process, the uncertainties and development needs are reckoned to be very high. One reason for this tight schedule could be the realization that the contribution CCS can make to lowering CO_2 becomes ever smaller, the longer it takes for the technology to be fully available.

If we take a look at the pilot and demonstration projects currently commenced or planned, adherence to the above time window appears quite possible, provided that the underlying economic and political conditions are favourable and targets are pursued resolutely (Table 7).

TABLE 7 COMMENCED AND PLANNED CCS PROJECTS (SELECTION)

When	What	Where	Who
2008	30-MWth oxyfuel power plant (commissioning)	Schwarze Pumpe/D	Vattenfall
2010	475-MW gas-fired power plant with CO_2 capture for EOR	Peterhead/GB	BP
2011	860-MW gas-fired power plant with CO_2 capture for EOR	Halten/Norway	Shell, Statoil
2011	IGCC with CO_2 capture and storage, southern North Sea	GB	E.on UK
2014	450-MW IGCC with CO_2 capture and storage in saline aquifer	D	RWE
2014	275-MW IGCC with CO_2 capture and storage in saline aquifer	US	»Future-Gen« project

EOR: enhanced oil recovery; IGCC: integrated gasification combined cycle

Source: own compilation

The timeframe for CCS to make a contribution to climate protection depends not only on the technical availability of the separation technologies, but also on the available storage capacities and the transport infrastructure. One other factor that must not to be neglected is the interplay of all the elements in the process chain, i.e. the geographic and temporal overlapping of the CO_2 to be captured and the availability of the transport infrastructure and storage sites. For example, oil and gas reservoirs that will go on producing for some time can only be used for CO_2 storage (or EOR) once they are sufficiently emptied or exhausted. Hence – if present trends are continued – the production situation of large oil fields in the North Sea would require CO_2 injection within the scope of EOR to commence around 2008 or so in order to beat the deconstruction of the infrastructure (POST 2005).

RETROFITTING WITH CO_2-CAPTURE TECHNOLOGIES 3.

As was described above, Germany and other industrialized countries as well will have significant power-plant renewal needs in the next two to three decades. In view of the fact that, pending the commercial availability of the CCS technology, new power stations will still be erected without separation technology, retrofitability of existing power plants with CO_2 capture systems will play an important role (OECD/IEA 2004a, p. 58).

Conventional coal-fired power plants could in principle be retrofitted with a downstream flue-gas scrubbing system (post-combustion) or with an oxyfuel process. In this respect, the post-combustion technology interferes least with the power-plant process: here, only a system for gas scrubbing (amine scrubbing in general) has to be installed and heat decoupled from the steam cycle that is required to regenerate the solvent. However, this does change the working conditions for the turbine, which must then be adapted for the most efficient operation possible. Also, the desulphurization of the flue-gas stream must come up to a high standard, since sulphur attacks the solvents.

Oxyfuel retrofitting requires a system to produce pure oxygen. In addition, the burners must be re-equipped to operate on oxygen, and flue-gas recirculation must be integrated into the combustion process. Also, it must be ensured that all components are compatible with the CO_2-rich working gas.

Power plants with integrated coal gasification (IGCC), too, can in principle be retrofitted: for this, the shift reactor of the gasification process must be set in such a way that the purest possible hydrogen and CO_2 emerge. The combustion properties of hydrogen make it inevitable that the core of a power station, its turbines, must be modified substantially or exchanged. Since the combustion of hydrogen produces much higher temperatures, a higher share of nitrogen oxide must be expected in the flue gas. Hence, adherence to emission thresholds requires additional denitrification measures.

A detailed analysis of the various technological options for retrofitting can be found, e.g., in IEA GHG (2007), which also formulates criteria that can be used to examine the question of whether retrofitting is a sensible step. The literature is widely agreed that, given today's state of the art, post-combustion flue-gas decarbonization is the most practicable option for any retrofitting.

Whether power plants are in fact retrofitted depends not only on the technological feasibility, but crucially on economic efficiency. Here, it must be noted that the retrofitting of power stations is a costly affair and is usually more expensive than integrating CO_2 separation into a new plant. Gibbins *et al.* (2005), for example, have calculated that the power costs of a conventional coal plant (efficiency without CCS: 43.5 %) would rise from about US$ 0.028/kWh to some US$ 0.058 after installation of a post-combustion CO_2 capture system.

CAPTURE-READY 3.1

At first glance, the idea of already designing power-station new-builds today in a way that will permit technically uncomplicated and low-cost retrofitting with CO_2-capture systems, as soon as the technology and the CO_2-storage areas required are available, looks an obvious and attractive proposition. This capture-ready concept is being much discussed in specialist circles at present, especially since the EU Commission has enriched the debate with the proposal that the only fossil-fired power plants to be approved in future will be those that are capture-ready (EU Commission 2007b). The Science and Technology Committee of the British House of Commons, too, advises: »We recommend that Government makes capture readiness a requirement for statutory licensing of all new fossil fuel plant.« (House of Commons 2006, p. 19). At the most recent G8 summits in Gleneagles and Heiligendamm, too, the capture-ready idea earned support (G8 2005, para. 14c, G8 2007, para. 72[17]).

In this connection, the immediate key issue is what a current power plant would have to look like to be deemed capture-ready. It comes as no surprise that this question finds no ready answer, since CCS technology is likely to be available on a commercial scale in about 15 years at the earliest. Until then, considerable uncertainties exist, both as regards technological further development and the underlying economic and regulatory conditions.

Hence, we are still quite at sea when it comes to the technical and/or economic criteria that a capture-ready power plant would have to meet. At present, we do not even have a generally recognized definition of the term »capture-ready«.

Bohm *et al.* (2007) define: »A plant can be considered ›capture ready‹ if, at some point in the future it can be retrofitted for carbon capture and sequestration and still be economical to operate.« A similar definition can be found in a current publication of the IEA GHG (2007, p. 2): »A CO_2 capture-ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place. The aim of building plants that are capture-ready is to avoid the risk of ›stranded assets‹ or ›carbon lock-in‹.«

One advantage of this kind of definition is that it is made clear that capture-ready is no technology in the narrower sense, but has in fact a strong economic reference. One obvious drawback is that no criteria are provided that could be used to check whether a plant to be built is capture-ready or not, since this depends on future economic or regulatory conditions – e.g. the price of CO_2 certificates or a retrofit duty. Strictly speaking, whether a plant is capture-ready or not could only be established retrospectively (if a retrofit has proved feasible).

The European Power Plant Suppliers Association (EPPSA) has recently published proposals on technical criteria for capture-ready plants (EPPSA 2006). One important prerequisite for CCS retrofitting being considered at all is that the power plant has a high initial efficiency, so that any efficiency loss caused by the capture can be borne. High efficiency also means that the amount of CO_2 generated is minimized and, hence, that the separation system can be scaled down.

17 Remarkably, the term »capture-ready« is missing in the German version of the document.

Next, the compatibility of the power-plant systems and components with the process parameters (e.g. temperature, pressure, composition and mass flow rate of the operating medium in the turbine), as changed by the separation system, must be ensured.

- For pre-combustion plants (e.g. IGCC), the requirements to be met by the gas turbine, the steam generator and by ancillary systems vary widely.
- For retrofitting with oxyfuel systems, flue-gas recirculation equipment must be installed, and measures taken so that all components can work with the CO_2-rich flue gas.
- Although retrofitting a power station with a CO_2 flue-gas scrubbing system (post-combustion) is the simplest option, it also has considerable implications for the design of the plant owing to the heat required for gas scrubbing (above all the steam cycle and its thermodynamics).

A power plant designed to operate with CO_2 separation would inevitably have substantial efficiency losses in the operating mode without separation, as well as higher fuel needs and, hence, a poorer economic and CO_2 balance sheet compared with a station that is optimized for operation without separation.

Current analyses unanimously recognize that (irrespective of the technology line chosen) the options for installing capture-ready components in the power plants to be built today are extremely limited (IEA GHG 2007). Significant up-front investment for later CO_2 capture would not generally be justifiable in economic terms – given the expected price range for CO_2-emission permits in view of the political measures being debated at present (Bohm *et al.* 2007). It would usually make better economic sense to build a conventional power plant and to retrofit extensively as soon as underlying conditions change (e.g. high CO_2 certificate prices) or – if that is not feasible technically or economically – to shut it down. MIT (2007a, p. 99) arrives at a very pessimistic assessment: »The concept of a ›capture ready‹ … coal plant is as yet unproven and unlikely to be fruitful.«

Only low-cost measures could be considered. These include, e.g., the provision of building land for the CO_2-capture plant and maintaining easy access to components that would probably have to be upgraded or exchanged in the course of retrofitting. Another possibility would involve making sure, in selecting sites for power plants, that these are close to a possible storage area or to existing infrastructure for CO_2 transport, or at least ensuring that no obstacles exist regarding the transport routes to a storage site (EPPSA 2006).

A robust assessment of whether the capture-ready concept is viable still requires considerable technical-economic analyses. Also, criteria must be developed that enable approval authorities, say, to assess the capture-readiness of power plants.

One interesting idea is to view capture-readiness detached from any technological debate, as a purely economic concept. This could mean, e.g., forming – precautionary – financial provisions during the operation of a power plant out of current receipts, so that sufficient funds are available for retrofitting as soon as the technology is deployable. To verify the feasibility of this approach, there is likewise urgent need for research.

MARKET DIFFUSION OF CCS TECHNOLOGIES 3.2

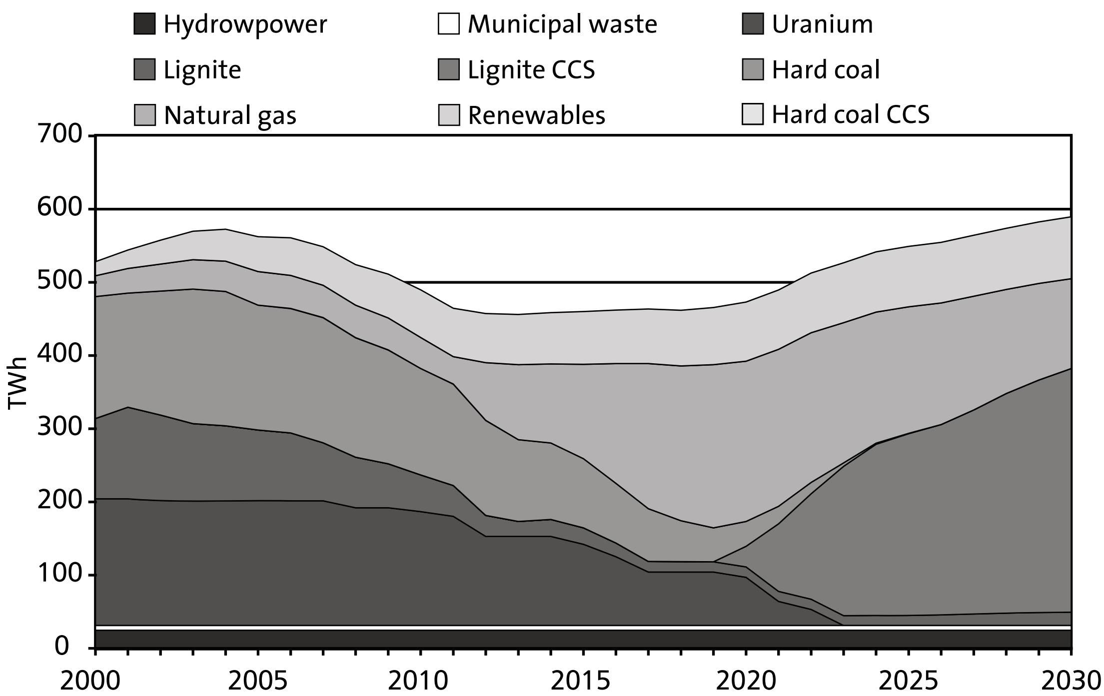
To answer the question as to the market opportunities for CCS technologies on the German electricity market, an in-depth model-backed analysis of their possible market diffusion was made within the scope of the TAB project. The account largely follows the expertise commissioned by the TAB from the Fraunhofer Institute Systems and Innovation Research (FhG-ISI 2007). This is also where further details on the model deployed and on the underlying assumptions made can be found.

The analyses were made using a model for the European electricity market based on the open-source model »Balmorel« (Ravn 2001). To make the model calculations easier to handle, the expected power generation from nuclear energy and renewables was considered given externally, and only the fossil-production options modelled. For nuclear energy, further implementation of the phase-out resolution was assumed; for renewable energies, the development path from the study by Ragwitz *et al.* (2007) was used. Also examined were the possible implications of changes in relevant underlying conditions (e.g. fuel prices, CO_2 reduction targets, time to market maturity for CCS, intensity of the efforts to save power, etc.) for market diffusion.

As the results in Figure 17 show, natural gas will become the most important energy source in power generation between 2010 and 2020, but will then lose this role quickly as CCS technologies become available and account for 60 % of electricity generation within one decade. For such a high share in total generation, a capacity of over 40 GW would have to be installed. Pursuant to these model results, eight to ten CCS-enabled large-scale power plants each would have to go on stream in the years 2020 and 2021, and between three and six each of such systems in the following years. Whether technology suppliers and the executing construction firms would be able provide power plants with CCS technologies on such a scale and at this pace is at least doubtful, as things stand today.

Even if such a rapid market penetration by CCS power plants were possible and the necessary CO_2-storage sites could be approved, such a scenario should be subjected to critical scrutiny. The amount of CO_2 to be stored in such a scenario would fast take on an order of many million tonnes per year. Very large CO_2-storage areas would be created in very little time without long-term experience of storage being available. This would contradict the philosophy of a careful development of risk-prone new technologies.

FIG. 17 POWER GENERATION BY ENERGY SOURCE (MODEL RESULTS)



Source: FhG-ISI 2007, p. 45

One possible strategy for perceptibly easing the time pressures on the erection of power plants with CO_2 capture would involve implementing measures for boosting energy efficiency and, in this way, lowering electricity demand. For this reason, measures designed to increase energy efficiency must be given a double positive rating, since, on the one hand, their effect relieves the climate balance, while, on the other, they help us gain time for generation technologies without creating path dependencies in the direction of particular technology lines.

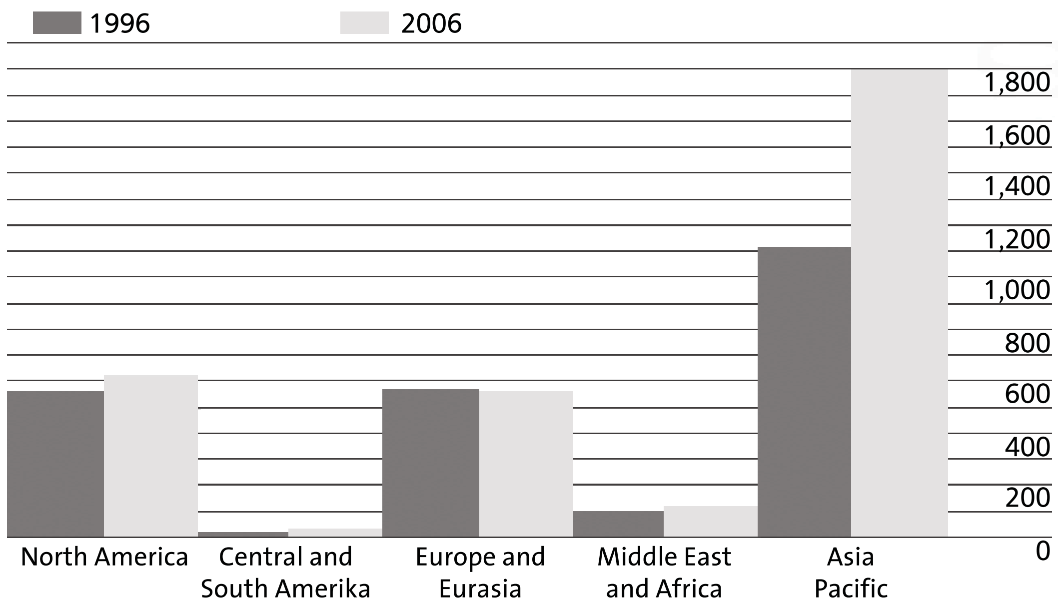
Overall, the results of the modelling suggest that, with the requirements of an effective climate policy, there will be a significant restructuring of the power-plant fleet.

INTERNATIONAL PERSPECTIVE 4.

The above Chapters having examined and assessed CCS technology mainly from a German or European angle, the next section will discuss what CCS could contribute to climate protection at an international level. Even if the conclusion is drawn – e.g. by the Study Commission on »Sustainable Energy Supplies in View of Globalization and Liberalization« of the 14th German Bundestag – that CCS »at all events« could »make only a very limited contribution in quantitative, temporal and regional terms to climate protection«, the situation is very different outside Germany or Europe.

In the Asian/Pacific region, for example, coal consumption rose by more than 60 % in the period from 1996 to 2006 (Fig. 18). This was due to the dramatic expansion of coal-based power generation in China and – to a lesser degree – in India[18]. In China alone, some 100,000 MW of fossil-fired power-plant capacity (mainly coal-based power stations) was built between 1995 and 2002. For the period from 2002 until 2010, it is forecast that another 170,000 MW will be added (Linßen *et al.* 2006, p. 40).

FIG. 18 COAL CONSUMPTION BY WORLD REGIONS (IN BN T OE)



Source: BP 2007, p. 33

These two countries have huge domestic coal reserves (China: 115bn t OE[19], India: 92bn t OE). In this, they are surpassed only by the US (with 247bn t OE) and Russia (157bn t OE) (BP 2007). If this consumption trend were to continue unchecked, the success of international climate-protection efforts would be imperilled in absolute terms. Hence, China and India are often fielded as examples

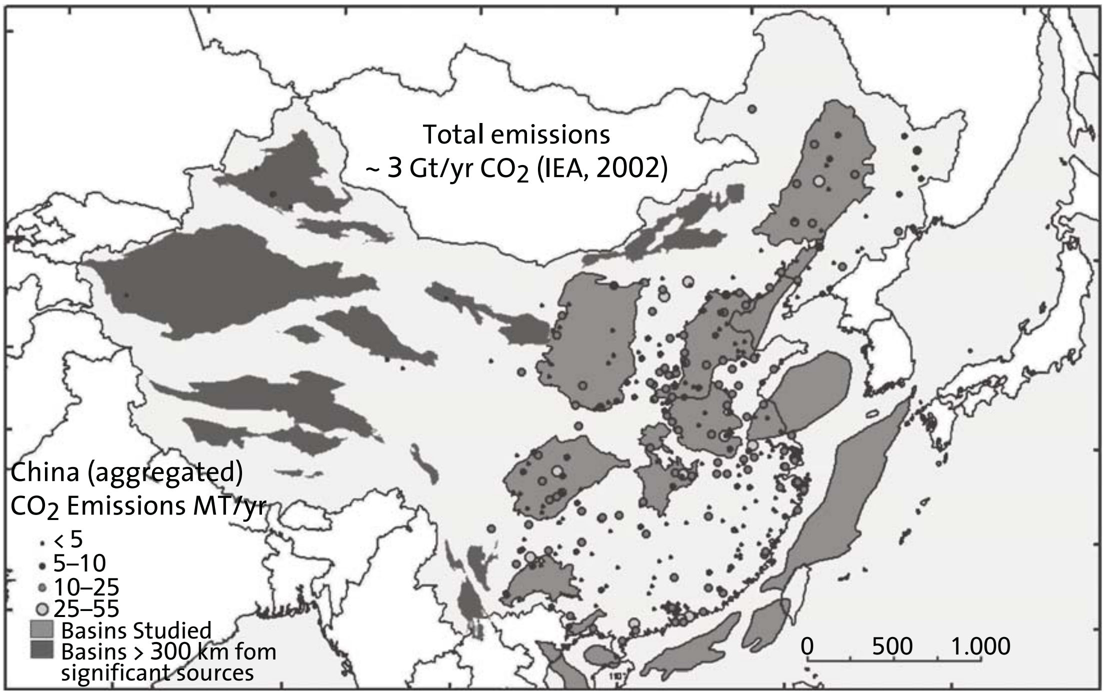
18 Although China and India are often named in one breath, developments in coal consumption in India are lagging China's by about two decades (MIT 2007a, pp. 63 ff.).

19 1 t oil equivalent (t OE) corresponds to roughly 42 GJ.

that CCS in certain countries could be an important component in achieving future climate-protection goals.

A broadly based launch of CO_2 capture and storage is rather unlikely in the short to medium term, however, at least with the current underlying conditions (OECD/IEA 2004a, p. 62). To make the deployment of CCS technology attractive in these and other emerging economies, it would first have to be successfully further developed and trialled. The most suitable candidates for this are industrialized countries with their technical know-how and financial clout. In the face of the immense dynamics of power-plant extensions, CCS must be launched as quickly as possible, since otherwise the window of opportunity will close and remain shut for many decades (Linßen *et al.* 2006, p. 40).

FIG. 19 GEOGRAPHIC LOCATION OF STATIONARY SOURCES OF CO_2 EMISSIONS AND SEDIMENT BASINS IN CHINA



Source: Rigg 2006

One important issue concerns the storage capacities available in various countries, on which hardly any robust information exists at present. An initial overview of selected sediment basins in China and Southeast Asia was drawn up recently (APEC EWG 2005). In China, there appear to be a number of promising candidate sites for possible CO_2 storage, some even in regions with a high number of emission sources (power plants) (Fig. 19). Whether these sediments are really suitable for CO_2 storage still requires in-depth investigation, however. So there is urgent need for research here. India, by contrast, has hardly any suitable geological formations on the mainland. There, offshore storage at best could be considered (IPCC 2005, p. 95).

What importance Chinese decision-takers attach to CCS technology is hard to read off at present. There are ambivalent signals here. First of all, CCS plays a leading role in the recently (June 2007) presented »National Climate Change Program« (NDRC 2007). Again, coal technologies and CCS form the centrepiece in the section »Energy and Environment« of the »Second U.S.-China Strategic Economic Dialogue« (TREAS 2007).

PUBLIC OPINION AND ACCEPTANCE V.

Public perception can have serious and unexpected implications for planned technology and infrastructure projects. Disputes – about nuclear energy and genetic engineering, say – bear eloquent witness to this. Technologies, like CCS, whose long-term risks to safety, health and the environment are hard to assess in places, are particularly apt to trigger public anxiety and possibly resistance.

Ensuring a high degree of public acceptance should be a high-ranking goal, therefore. This was also the conclusion drawn by a hearing recently held in the British House of Commons. A representative from BP put it in a nutshell: lack of acceptance could be a »potential show stopper« (House of Commons 2006, p. 41). One important precondition for social acceptance is the creation of transparency by ensuring comprehensive information both about the sense and purpose of CCS in general and about concrete schemes and projects. As the past has shown, however, information and advertising alone are by no means sufficient for creating acceptance. To avoid acceptance and trust crises, therefore, an open-ended dialogue process between industry, stakeholders, science and the public should be organized early on (ACCSEPT 2006; EU Commission 2007c). Broad consensus on this exists among CCS specialists in Germany.

The deployment of CCS in power generation has been discussed increasingly as of late and, in places, controversially by opinion leaders in Germany. Misgivings are voiced in particular by environmental associations and, in the political arena, by the Greens and the Left Party, while the conservative, social-democrat and liberal camps (CDU/CSU, SPD and FDP), as well as industry are largely positive in their assessment of the use of CCS. What follows is an account of the positions taken by some scientific societies and advisory bodies, environmental associations, the parties represented in the Bundestag and the ministries in charge (WD 2006, pp. 37 ff.; WI/DLR/ZSW/PIK 2007, pp. 36 ff.). Also cited are the results of recent empirical polls (surveys and focus groups) on the perception of CCS among stakeholders and in the general public.

Proceeding from the diagnosis that there has, so far, been no systematic communication, discussion or consultation strategy that takes up the crucial points in the debate, one possibility is suggested in the sequel of how such a process to promote social acceptance of CCS technology might be structured.

POSITIONS OF STAKEHOLDERS 1.

SCIENCE, ADVISORY BOARDS

The *Intergovernmental Panel on Climate Change (IPCC)* is assuming that it is technically feasible to avoid 20 to 40 % of global carbon-dioxide emissions by 2050 using CO_2 sequestration. The risks for people, the environment and the climate are viewed as being low overall, and the chances of the CO_2 remaining in geological traps permanently for over 1,000 years and longer as high (IPCC 2005).

The *German Council for Sustainable Development (RNE)* has spoken out in favour of CO_2 capture and storage. It could make a contribution, the Council said, toward the continued use of coal for power generation in Germany, while nonetheless allowing the climate-protection targets to be reached by the middle of the century. As the Council sees it, using clean coal builds an important bridge between fossil and renewable energies (RNE 2003, pp. 20 ff.).

The *German Advisory Council on Climate Change* (*WBGU*) sees as long-term aim a switch from fossil to renewable-energy sources. For a transition period, it would be necessary to go on using fossil fuels. It is regarded as being »probably inevitable« that such use is a concomitant of techniques for CO_2 capture and safe final depositing in suitable storage areas. Storage should only be in geological formations in which a leakage rate of less than 0.01 %/year can be guaranteed or if the retention time is at least 10,000 years. The WBGU suggests that power-plant expansion should focus on highly efficient gas and steam power stations that can be retrofitted with CO_2 capture and offer the possibility of integrated gasification of coal and biomass (WBGU 2007).

The *German Advisory Council on the Environment (SRU)* does recognize that CO_2 capture and storage offers a possibility in principle of making coal-based power generation compatible with climate protection. However, its economic application maturity could hardly be expected by 2020, so that it would come too late for the upcoming renewal of wide sections of Germany's power-plant portfolio. It is stressed that many questions concerning the extent and scale of CCS deployability are still open. Open in particular, it was said, is the question of whether permanently safe and, hence, final storage that is acceptable in environmental-policy terms as well is possible on a large scale (SRU 2004).

The *Sustainability Council of the Baden Württemberg State Government (NBBW)* is of the opinion that the deployment of low-CO_2 or zero-CO_2 power plants can make a crucial contribution to environmental and climate protection. In addition, »clean« coal-fired power stations have the advantage that they could secure the basic energy supply (the so-called base load) in the long term more readily than various renewable energies (wind, water, solar). The NBBW is in favour of stepping up support for research and suggests initiating a »beacon project« in which the entire CCS process chain is demonstrated on a large scale. It points out that – even if high storage safety can be guaranteed – a fundamental unease in the population might remain if large amounts of waste are to be stored underground for a long time (NBBW 2007).

From the general sustainability criteria, which the Study Commission »*Schutz des Menschen und der Umwelt*« (Protection of humans and the environment) of the German Bundestag produced in the 13^{th} electoral term (EK, 1998), Germany's *Federal Environment Agency* (*UBA*) has derived criteria for CCS and noted these in seven propositions (UBA 2007):

Proposition 1: Climate protection can be achieved with renewable energies and energy efficiency. Technical CO_2 capture and storage, by contrast, is not sustainable, but a transition solution at best.

Proposition 2: The capacities for CO_2 storage belong at the centre of the debate: in Germany, they could be limited to 40 years in purely mathematical terms.

Proposition 3: Technical CCS involves costs. Some projects will probably pay off, however – ambitious climate-protection targets provided.

Proposition 4: CO_2-storage sites should not exceed a leakage rate of 0.01 %/year. Health and environmental hazards must be avoided.

Proposition 5: The storage of CO_2 in the ocean water column and »artificial mineral carbonation« of CO_2 are no options.

Proposition 6: A national and international legal framework for CCS must be developed.

Proposition 7: Environmental and fairness aspects must form part of the debate. Research, state regulation and demonstration projects must not just confine themselves to technical aspects.

The *Association of German Engineers (VDI)* mainly favours technologies that reduce CO_2 via an increase in power-plant efficiency. With CO_2-certificate prices at around Euro 30/t, however, lignite-based power generation with CO_2 capture would be profitable and – except for nuclear technology – superior, in terms of economic efficiency and security of supply, to other technologies for power generation in Germany. Hence, the erection of pilot plants is supported, and the large-scale demonstration of market maturity deemed necessary after 2015 (VDI, no date).

The Working Group Energy Matters (AKE) of the *German Physical Society (DPG)* is of the opinion that there is justified hope that sequestration will make a very significant contribution toward solving the CO_2 problem. In view of the climate problems, CO_2 sequestration could be regarded as the only route available at all if we are to make use of fossil energy sources without harming the climate. CO_2 sequestration is said to have »good prospects of becoming one of the least-cost techniques to avoid CO_2.« (DPG 2005, pp. 71 ff.).

The *German Chemical Society (GDCh)* is critical of geological sequestration due to the immense need for research and the high costs involved. Increased reforestation of large wooded areas is viewed as the most effective alternative to CO_2 trapping (Hüttermann/Metzger 2004).

ENVIRONMENTAL ASSOCIATIONS

The positions of environmental associations and other non-governmental organizations (NGOs) cover a wide spectrum ranging from support for CCS subject to definite conditions, all the way to complete rejection. Nonetheless, there are indications of a certain mainstream, which is discernible, e.g., in a joint declaration by the Bund für Umwelt und Naturschutz Deutschland (BUND – Friends of the Earth Germany), Deutscher Naturschutzring (DNR), Forum Umwelt & Entwicklung, Germanwatch, Klima-Bündnis (European office), klimamarsch, Naturschutzbund Deutschland (NABU), Verkehrsclub Deutschland (VCD) and by WWF Deutschland (World Wide Fund for Nature) (Germanwatch 2003). Similar arguments are fielded by the umbrella organization Climate Action Network Europe, in which a number of German NGOs are organized as well (CAN Europe 2006a): CO_2 sequestration is regarded as classic (post-closure) end-of-pipe technology which makes the use of conventional, fossil-fuel sources more expensive and, due to a fall in power-plant efficiencies, increases fuel consumption. This, it is said, clashes with the priority aim of a resource-sparing energy supply. Only if CCS could make an additional contribution in ambitious climate-protection targets and if its long-term security is proven, could CCS be considered as an option for action. Carrying out research projects to clarify open issues is accepted, although it cautions that promoting CCS technology must not be at the expense of renewable-energy sources and rational energy utilization. A consideration of CCS projects under CDM (Clean-Development Mechanism of the Kyoto Protocol) is rejected (CAN Europe 2006b).

POLITICS

The positions of the political parties on the subject of CCS are currently beginning to take a clearly recognizable shape. After the energy Study Commission of the 14th German Bundestag had accorded the subject of CCS no central importance five years ago and arrived at the fairly sober judgement that CCS was »a rather medium- to long-term *vision*« (emphasis in the original), which »at all events« could »make only a very limited contribution in quantitative, temporal and regional terms to climate protection« (EK 2002, pp. 255 and 258), the parties represented in the Bundestag are adopting much more differentiated positions today:

The *CDU/CSU parliamentary group* in the *Bundestag*, in a position paper on climate change, has stressed CCS technology as one focus in the research and development of climate-protection technologies. This would yield new options for environment-sparing power generation from fossil fuels. The standpoint is that both existing coal-fired power plants and new-builds should be fitted with CCS technology as soon as this technique is available (CDU/CSU 2007).

The *SPD parliamentary group* in the *Bundestag* calls for greater investment in R&D for efficient and competitive use of power plants with CO_2 capture and storage, and the creation of legal and economic conditions, so that only zero-CO_2 power stations go on stream after 2015/2020. However, any up-front decision in favour of CO_2 capture as a real option should be avoided. It must first demonstrate its technical, ecologically compatible and economic implementability (SPD 2007).

The *FDP parliamentary group* has tabled a motion in the Bundestag with a diagnosis that CCS is the previously missing link between a conventional and a completely renewable-energy supply and could help lengthen the timeframe available for transforming the energy system, while achieving ambitious climate-protection targets. The party demands a comprehensive strategy for the use and further development of CCS technologies, which should be pursued under an overall energy-policy concept (FDP 2007a).

In its recently published energy concept, the *Alliance 90/The Greens Bundestag parliamentary group* refers to low-CO_2 coal-fired power plants as a »much-cited energy-policy vision with numerous technical and economic imponderables and question marks«. Even if all technological and financial problems were solved, CCS-equipped power stations could make no relevant contribution to the energy supply in 2020 either, since the technology would not be commercially deployable by then. Also, the parliamentary group demands a moratorium for coal-based power plants without CO_2 capture (Alliance 90/The Greens 2007a). Moreover, CO_2 storage in geological traps below the sea is only to be permitted if any risks regarding environmental compatibility have been previously ruled out (Alliance 90/The Greens 2007b).

The *Left Party Bundestag parliamentary group* goes one step further and sees in CO_2 injection a »Trojan horse of the coal industry«. CCS, it is said, is an »expensive experiment with an ecologically uncertain outcome«, and the research funds for CCS would be much better spent as subsidies and research aid to expand the renewable-energy supply and improve energy efficiency (Left Party

2007a). Operating permits of indefinite duration for power plants (without CHP) should only be issued if a threshold value for CO_2 emissions is adhered to that is similar to the value applying to modern natural-gas-fired power plants (Left Party 2007b).

This ongoing formation of opinion among the parties is also reflected in a stepping up of Bundestag activity. In the recent past, CCS has time and again been mentioned in energy-policy debates (e.g. German Bundestag 2007a and b). Again, the Committee on the Environment, Nature Conservation and Nuclear Safety held a public hearing on the subject on 7 March 2007 (AUNR 2007), and a number of motions have already been tabled in the Bundestag (Alliance 90/The Greens 2007b; Left Party 2007b; FDP 2007a and 2007b), and several interpellations formulated (Alliance 90/The Greens 2007c and 2007d; CDU/CSU 2004; FDP 2007c).

The Federal Government has documented its position in its Answer to a Minor Interpellation and elsewhere (Federal Government 2007). It reckons that the commercial use of CO_2 storage could be possible by around 2020. This would depend on the results of current R&D projects, however. The Federal Ministry for Education and Research promotes CCS research within the scope of its »Geotechnologies Programme«, while the Federal Ministry of Economics and Technology has one promotion focus in its »COORETEC Programme«. The Federal Environment Ministry is of the opinion that »no later than 2020 ... CCS technology for the safe capture and storage of CO_2« should »be the standard for all new fossil-fired power plants« (BMU 2006).

PERCEPTION AMONG STAKEHOLDERS: SURVEY RESULTS

Two surveys were published recently which examined stakeholders' assessment of CCS technology:

One poll, conducted within the scope of the »ACCSEPT« project, covered 511 stakeholders (from the energy industry, research, governments, parliamentarians and NGOs) in many European countries. Asked whether CCS was necessary for achieving climate-protection targets in their home country, 40 % said »definitely necessary«, 35 % »probably necessary«, 12 % »only necessary if other options fail to live up to current expectations«. Only a small number of the respondents said that CCS was »probably not necessary« or »definitely unnecessary« (8 % and 4 % resp.). The risks associated with CCS were mostly said to be »moderate« or even »negligible«. A relatively large number (44 %) voiced concern that investment in CCS would have a negative effect on other low-CO_2 technologies; a narrow majority (51 %) did not share this opinion. A similar response was obtained to the question about the effect CCS could have on a decentralized energy system.

A breakdown of the results by stakeholder group is interesting: as expected, the participants from industry were the most positive in their response, and those from NGOs most sceptical about the possible role of CCS. It does come as a surprise, though, that the answers from scientists were nearly as optimistic as those of industry representatives, while the parliamentarians questioned tended to be sceptical-to-pessimistic (although a mere 21 parliamentarians in all took part in the survey) (ACCSEPT 2007).

The EU Commission has conducted an Internet-based consultation »Capturing and storing CO_2 underground – should we be concerned?« Among the 800 or so participants – nearly all climate/energy specialists and mostly CCS insiders (80 %) – the question of whether CCS could be regarded as ranking equal with other options for reducing greenhouse gases met with a divided response: some 52 % said »yes«, 46 % »no« (2 % don't know). By contrast, the proposition »Nuclear energy is the better solution for low-CO_2 power than CCS« was rejected (62 %, with 30 % agreeing and 8 % abstentions). A high level of support (some 70 %) was found for the following statements: »Before 2020, all new fossil-fuel power plants built should be ›capture ready‹, »All ›capture-ready‹ plants should be retrofitted soon after 2020« and »From 2020 onwards all new coal-fired power plants should be built with CCS«. There was even more agreement (over 75 %) on the question of whether the EU should support 12 full-scale demonstration projects by 2015 (EU Commission 2007d).

PERCEPTION BY THE PUBLIC

Although the debate surrounding CCS in specialist circles has definitely gained in intensity and momentum lately, the subject hardly seems to be interesting the general public. As representative surveys show, a mere 5 to 10 % of the population (in the US, Japan, the UK and Sweden) has even heard of CO_2 capture and storage and, of those, only a small minority was able to correctly identify the environmental problem that CCS is supposed to help reduce (MIT 2007b; Reiner *et al.* 2006). A trend was revealed showing that support for CCS grows perceptibly when additional information about the technology and its link with the greenhouse effect and climate change is offered. In fact, the number of participants with a positive attitude to CCS rose from 13 to 55 % when such information was given. Although support for renewable energies was even higher (90 %), CCS then came off much better than nuclear energy (24 %) (ETP ZEP 2006b).

Due to this low level of knowledge among the public, it is understandable that no broad-based discussion of CCS is taking place. For the formation of public opinion, therefore, the success or failure of the first CCS project could be trend-setting.

PROMOTING ACCEPTANCE 2.

The measures for public consultation prescribed by law – as applied, e.g., within the scope of approval procedures – do have the advantage that their inclusion in the procedure and their binding effect are known in advance and clearly defined.[20] However, one major drawback is that the measures for public involvement do not kick in until a relatively advanced planning stage in which many details of the implementation of a plant or measure have already been worked out by an applicant. As a result, they come to bear at a stage when many decisions, specifically fundamental considerations of whether, how and where a measure is to be taken, have already been made.

Experience in the implementation of major projects has shown that, besides the formal planning and approval events, a comprehensive information and participation strategy is a sensible idea. Innovative information and participation measures (e.g. mediation procedures) have been taken on various occasions in the approval of large-scale projects, e.g. in connection with the extensions to the airports in Frankfurt and Vienna and in the search for final storage sites for radioactive waste in various countries (e.g. Belgium, Switzerland, Sweden, Finland) (Öko-Institut 2007, pp. 148 ff.).

What follows is the development of a proposal for a national, location-independent participation process closely dovetailed with regional activities. In view of the advanced time schedule for upcoming exploration and pilot projects, there is an urgent need for action to initiate such a process. This opinion was shared by all participants in the workshop of experts mounted by the TAB on 18 January 2007.

The aim of the national involvement process is to trigger a social or political discourse on CCS to anchor the subject as far as possible in public awareness before the planning for potential site regions takes a concrete form. This would increase the level of public information and enhance the transparency of the process. Another task would be to seek the most far-reaching agreement possible among stakeholders and to clarify the final shape, jurisdictions and participation, and the financing of further procedure.

One initial milestone worth aiming at swiftly would be an understanding among stakeholders on the importance of CCS for climate mitigation. Broadly backed agreement on the role of CCS in the climate-mitigation portfolio would create a sound basis

20 This chapter is essentially based on the expertise commissioned by the TAB from Öko-Institut (Öko-Institut 2007).

- for the drawing up of recommendations for the fundamental requirements to be met by CCS (e.g. legal framework, protection goals, safety criteria, liability and monitoring, the approach to potential conflicts of use and the valuation of CCS in emissions trading) and
- for clear signals from policymakers to implement this strategy.

One possible way to organize this process of understanding would be a national »CCS forum«. At the moment, the number of stakeholders actively involved in the CCS debate at national level is fairly small. Accordingly, it should be possible to bring together all relevant opinions in an approx. 20-strong forum. Besides defining the precise distribution of roles and responsibilities, one first issue to be clarified would be that of who could act as initiator or organizer of such a forum. Since neutrality is a crucial prerequisite for the credibility and success of any body of this kind, the future operators of/applicants for CCS plants are not ideally suitable as initiators. Among the more suitable institutions, the TAB workshop of experts proposed the Federal Environment Minister (or the Federal Environment Agency), the Forum of Future Energies, the COORETEC advisory board, or the German Council for Sustainable Development. It would also be feasible to place the forum as an independent body directly in the sphere of responsibility of the Chancellery, since the concerns of different departments are affected. It would certainly be helpful if some well-known personality with a positive public impact could be won over to chair the forum.

The need for specialist, in-depth treatment of possible consultation topics suggests the setting up of smaller task forces able to focus on specific themes; they would report their results to the CCS forum. Such a working mode is also to be recommended in view of the tight timeframe available for the national process of involvement, since fundamental issues would have to be clarified in this setting before any activities are commenced in the various regions.

In addition, the national process of involvement should be accompanied by information activities for the general public that thematize the role of CCS in reaching climate targets and other important aspects. Precisely because no clear positions have formed as yet in the public mind, this approach has great potential for gaining public trust by ensuring comprehensive, target-group-geared information and a fair, transparent process, and for developing public acceptance of any planned measures.

Since, as we are well aware, it makes a huge difference whether someone is in favour of a certain project in principle, while rejecting implementation in his own backyard, it is vital that a regional process of involvement be triggered before specific siting decisions are upcoming, let alone already made. As things stand today, processes of involvement must be established particularly in those regions where planning calls for activities that point to (potential) commercial use for CO_2 storage underground. These activities start with the exploration phase to identify suitable sites that must be expected in the relatively near future already.

Implementing pilot projects in an affected region might be viewed less critically, so that acceptance requirements might be reduced here. In this respect, however, account should be taken of the possible effect in predetermining pilot projects for later commercial use.

This being so, the process should be backed by preparatory and flanking measures at national level and by clear political signals for the need to use CCS. The following measures could be fundamental in a regional process of involvement:

- The aims of the process of involvement for the commercial use of CCS are the formulation of the site-specific requirements to be met by implementation, as seen by the region, and the negotiation of compensation measures.
- The region affected/to be involved must be identified, with a breakdown by area in the environs of the injection points and by the other areas above an extensive storage formation. The size and location of the region to be involved depend on the potential implications of the project, taking account of the location and spatial extent of the potentially suitable region.
- The general public is informed, e.g. by brochures, Internet offerings, media and info events, and actively involved in the process by way of discussion events, citizen forums and dialogues on specific subject focuses with all interested citizens.

In deciding the scope and depth of involvement measures, it must be borne in mind that one specific property of CO_2 storage concerns the large size of the potential reservoirs. A geological formation can extend across an area of over 100 square kilometres. In principle, therefore, a corresponding area above this formation may be affected, even if any impact on humans or the environment can be ruled out from a scientific angle. Where social acceptance is lacking, this may mean that a multitude of objections are raised against a project (experience has shown that the number can reach an order of 100,000 and more, as in the case of the expansion of Berlin-Schönefeld airport) and decisions are considerably delayed by lawsuit options. This being so, heed must be paid at an early stage to those areas in a potential site region where an active exchange of information should be sought with the population and stakeholders in order to minimize the scope of any intervention and to ensure the most amicable possible implementation of the project.

LEGAL ISSUES VI.

For the testing, introduction and diffusion of CCS technology, a suitable regulatory framework must be created, which should have three simultaneous aims: 1) to establish the conditions for the *admissibility* of the various components of CCS technology (capture, transport, storage); 2) to provide *incentives* for investing in CCS technology; and 3) to ensure that CCS does not fail for lack of public *acceptance* in general and at the storage sites in particular.

What follows starts by discussing the tasks of a legal framework for CCS. This is followed by an analysis of the stipulations of existing laws and ordinances and of the deficits that exist in the regulation of CCS, and concludes with a description of the final shape that a future CCS legal framework could have. This assumes that there is a public interest in the further development and deployment of CCS – mainly for reasons of climate protection. However, it cannot be ruled out that this assumption could be modified or even revised in light of future experience and knowledge. This account is based mainly on the expertise commissioned by the TAB from Öko-Institut (Öko-Institut 2007).

TASKS AND OBJECTIVES OF A LEGAL FRAMEWORK FOR CCS 1.

Irrespective of the issue of the shape eventually given to the future legal framework for CCS, it should pursue the following general tasks and objectives (see also the thinking in OECD/IEA 2007, pp. 25 ff.):

- The legal prerequisites must be created so that CCS can be implemented as one option for achieving climate-protection targets in Germany.
- The attraction of CCS for private project developers should be restricted as little as possible, or promoted by providing incentives.
- It is necessary to clarify how regulatory account can be taken of the existing interdependencies between capture, transport and storage.

The law at present offers no procedure either for the *exploration* of *storage sites* or for CO_2 *storage*. Hence, the rules to be created would have to:

- enable research/development and trial projects at short notice, so that further findings for commercial-scale use are gained and still-existing uncertainties eliminated (e.g. behaviour of CO_2 underground after injection and the risks of CO_2 storage);
- ensure that projects can only be approved if hazards for humans and the environment are ruled out, or adequate prevention measures are taken;

- in the concrete underground exploration of potentially suitable CO_2-storage sites: resolve any conflicts of use with land owners and competing projects – in view of the fact that the storage sites may affect an area of many square kilometres;
- make a contribution toward building trust and public acceptance of CCS technology, specifically by involving public and private stakeholders as well as the general public, and by weighing up all public and private concerns in the approval procedure.

The legal framework would also have to remove existing regulatory uncertainties and gaps, e.g. in the classification of CO_2 as waste, the liability for personal loss or injury and environmental damage from CCS projects, or the applicability of environmental-impact assessments (EIAs). Clearly defining the rights and duties of all actors involved should create a maximum in the way of legal certainty for the development and market launch of CCS technology.

The creative leeway for national legislators is predetermined in places by international duties and European regulations. In the EU, there are currently activities under way to develop a common European stance in regulating CCS projects (EU Commission 2007b, pp. 8 f.). Of course, the normative standards of European and national law must be taken into account, inter alia the precautionary principle, the polluter-pays principle, avoidance of hazards, as well as sufficient involvement of the public.

ANALYSIS OF THE CURRENT LEGAL FRAMEWORK 2.

The present legal situation contains no provisions whatsoever explicitly created for CCS technology or designed to apply to it exclusively. Rather, existing regulations are marked by having various single (environmental-)law provisions also covering different CCS facts. On the one hand, the result is the existence of *demarcation difficulties* between existing regulatory areas, so that the scope of the laws in question will have to be carefully examined while, on the other, there are *regulatory gaps* that must be closed to ensure adequate legal standards in applying CCS technology. An overview of the relevant regulatory areas for the entire CCS technology chain (capture, transport, injection and storage) discussed in more detail in what follows is given in Table 8.

TABLE 8 REGULATORY AREAS RELEVANT FOR THE CCS TECHNOLOGY CHAIN

Process	Regulatory areas affected	Relevant laws/ ordinances	Assessment
Capture			
	Pollution control	BImSchG/BImSchV	Construction of capture systems subject to approval
	Handling of waste	KrW-/AbfG	Must be applied if CO_2 is classified as waste
Transport			
	Transport of waste	KrW-/AbfG	Must be applied if CO_2 is classified as waste
Marine transport	Hazardous goods on sea	GGVSee	Must be applied
Pipeline	Environmental compatibility	UVPG	Lays down general protection standard
	Safety of pipelines	RohrFLtgV	Must be applied
Injection and storage			
	Mining and similar underground activities	BBergG/UVP-V	Not applicable in current form
	Handling of waste	KrW-/AbfG	Must be applied if CO_2 is classified as waste
	Pollution control	BImSchG/BImSchV	Provisions applicable to systems not subject to approval
	Water/groundwater protection	WHG/GrWV	Discharge of CO_2 subject to approval
	Soil protection	BBodSchG	Might apply

Source: own compilation

CO_2 CAPTURE 2.1

POLLUTION CONTROL

Building a new power station or industrial plant is subject to approval pursuant to Germany's Federal Pollution-Control Act (BImSchG). An associated plant for capturing CO_2 must be classified as an environmentally relevant secondary installation, so that it is fully covered by approval requirements (sec. 6(1) BImSchG). In any subsequent erection (retrofitting) of a CO_2-capture system, it must first be examined whether this constitutes a material change to the plant (sec. 16(1) BImSchG). If this is the case, the relevant protection and precautionary duties must be met.

The state of the art in CO_2 capture has not been defined so far in the implementing regulations and would have to be worked out urgently for any full-scale CCS application.

WASTE LEGISLATION

Before we can answer the question of whether waste legislation applies to the further handling of CO_2 after its capture (i.e. its transport, injection and storage), we must clarify its legal status: is CO_2 to be classified as waste, or perhaps as an emission or a product? Classification has direct legal implications: if CO_2 is classified as waste, one consequence will be that its transportation is subject to the provisions[21] of waste legislation, and the erection of plants for injecting and storing CO_2 may be subject to a formal public planning procedure[22].

According to the definition of the term »waste« in German law (sec. 3(1), sent. 1 KrW-/AbfG) (which is crucially determined by EC law[23]), waste refers to:

> all »movable property« (chattels)
> that falls within one of the groups listed in the Act[24] and
> that the owner disposes of, or wishes to dispose of (subjective waste concept) or
> that the owner must dispose of (objective waste concept).

CO_2 in gaseous form without any container is not a »thing« (*Sache*) as defined by German law (sec. 90 BGB). Legally, CO_2 must be treated as a »thing« (corporeal object) if it can be delineated spatially (i.e. if it is enclosed by a container, say) or if it exists in liquefied form. So, assuming a will to dispose (*Entledigungswillen*), liquefied CO_2 and gaseous CO_2 in containers are waste within the meaning of the Waste-Management Act (sec. 3(1) KrW-/AbfG). If the CO_2 is contaminated by pollutants, thus constituting a potential hazard, the objective waste concept (see above) would apply.

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21 FN 21 See the regulations on the supervision of waste in sec. 40(1) KrW-/AbfG; the regulation (EEC) No. 259/93 on the supervision and control of shipments of waste within, into and out of the European Community (OJ L 30 dated 6.2.1993, pp. 1–28) as well as the Waste-Shipment Act dated 30.9.1994, Federal Gazette I, p. 2771; most recently amended by Ordinance dated 31.10.2006, Federal Gazette I, p. 2407.

22 If the plant is classified as a waste-disposal plant pursuant to secs. 30 ff. KrW-/AbfG.

23 Cf. the definition of the term »waste« in Article 3 letter (a) of Directive 2006/12/EC.

24 Annex I to sec. 3(1) KrW-/AbfG.

EXCURSUS: LEGAL STATUS OF CO_2 IN EXISTING PROJECTS FOR CO_2 STORAGE INSIDE AND OUTSIDE GERMANY

- The CO_2SINK project in Ketzin (near Potsdam) did not specify whether the injected CO_2 is to be treated as an industrial or a waste product, since only a relatively small amount is concerned (totalling 60,000 t CO_2 in food quality).
- The planned Australian Gorgon project views CO_2 as a by-product in gas processing.
- In the In Salah (Algeria) project, CO_2 is deemed to be an industrial product, as it is in the RECOPOL project (Poland).
- The Sleipner project (Norway) defines CO_2 as an industrial item, since it emerges as a result of industrial activities. However, this was contentious in view of the intention of long-term storage.

Source: OECD/IEA 2007, p. 29

Pipelines are not containers within the meaning of the Act (sec. 2(2), no. 5 KrW-/AbfG). So, if gaseous CO_2 is to be transported by pipeline, the Act would not apply. For CO_2 storage, too, the distinction has consequences: any storage of gaseous CO_2 without container would not be subject to the waste regime, while storage in a liquefied form certainly would.

TABLE 9 CLASSIFICATION OF CO_2 UNDER WASTE LEGISLATION

Specification	Waste-legislation classification
Gaseous CO_2 (not enclosed)	Waste legislation does not apply
Gaseous CO_2 in containers	Waste legislation applies
Liquid CO_2	Waste legislation applies
Supercritical CO_2 (liquid or gaseous)	Unclaer

Source: Öko-Institut 2007

For transport (and storage as well), however, it is the supercritical phase that is best suited from a technical angle. Whether this aggregate state can be placed in the same category as the liquid or the gaseous state requires urgent clarification in legal terms (Table 9).

CO_2 TRANSPORT 2.2

Depending on the transport mode chosen, different regulations must be heeded. What follows only addresses pipeline transport and overseas transport by ship, since it is foreseeable that other options (tanker truck, inland shipping) will not be playing a major role.

If *transport* is *by ship*, the safety requirements of Germany's Regulation Concerning the Carriage of Dangerous Goods by Marine Vessels (GGVSee) must be met, since CO_2 must be classified as a hazardous good within the meaning of this Regulation. *Transporting* CO_2 by *pipeline* is regulated by the general protection standards laid down in Germany's Act on Environmental-Impact Assessments (secs. 20 ff. UVPG), which are given concrete form in the country's Ordinance Regulating Pipeline Installations (RohrFLtgV)[25]. At any event, where large amounts of CO_2 are transported by pipeline through densely populated regions, the existing regulations for transporting gases must be examined to identify the requirements that must be met in the way of safety and retainability.

CO_2 INJECTION AND STORAGE 2.3

For CO_2 injection and storage, numerous issues from various areas of law must be clarified. These include pollution-control law, waste-disposal law, mining law as well as certain aspects of water- and soil-protection law. Specifications under international law may also have to be heeded.

STIPULATIONS UNDER INTERNATIONAL LAW 2.3.1

International law is relevant mainly for CO_2 storage in layers of the seabed, while onshore storage is on national terrain where national law must be applied.[26] The treaties of relevance for Germany are the London Convention and its Protocol, the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) as well as the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention, HELCOM).

Since these treaties were concluded long before CCS was considered in climate mitigation, it was at first unclear whether CO_2 storage in deep geological strata below the seabed would be admissible under international law. This need for elucidation was recognized[27] early on, and both the London Protocol and OSPAR were recently supplemented to take this into account.

25 Germany's Ordinance Regulating Gas High-Pressure Pipelines (GasHDrLtgV), too, might apply if CO_2 is to be transported in the gas-supply networks of the energy utilities.
26 National law also extends to coastal waters and to the continental shelf. If projects cross borders, bilateral coordination must be sought.
27 For the London Convention: 2004; for OSPAR: 2002.

The London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) aims at reducing marine pollution from waste produced on land. Its Protocol is no mere supplement to the London Convention, but replaces it for the Contracting Parties that have ratified it (so far, 31 countries, incl Germany).[28] The London Protocol bans the dumping of industrial waste in the sea from ships and offshore platforms. This includes the seabed and the subsoil. Discharge via onshore pipelines would be allowed, provided that such discharge is managed in such a way that an approval would be needed and that regulations are made that prevent any pollution of the marine environment.

As CO_2 was not on the »reverse list« of substances for which a discharge permit can be considered and possibly issued[29], it was unclear until quite recently whether CO_2 storage in deep seabed layers would be permissible under the London Protocol. The reverse list was then supplemented in November 2006 to include »carbon dioxide streams from carbon dioxide capture processes for sequestration«. However, the streams must overwhelmingly consist of carbon dioxide[30] and may only contain incidental associated substances derived from the source material and from the capture process used. On no account must waste or other matter be added for the purpose of disposing of them. In November 2007, guidelines are to be adopted that are designed to make sure that, in any CCS activities, the aims of the London Protocol are heeded and that the short- and medium-term safety of the marine environment is ensured (IMO 2007).

Legal uncertainty, too, was addressed by the OSPAR Convention. The Parties to the Convention clarified the open questions as regards CO_2 storage in June 2007. Accordingly, storage in the sea and on the seabed is banned, while storage in geological seabed strata is permissible, albeit subject to rigorous requirements (OSPAR 2007).

As things look so far, HELCOM has not yet given any consideration to the question of how CCS activities might be squared with the Convention. However, since the OSPAR Convention often serves as a model for other international treaties dealing with the protection of the marine environment (OECD/IEA 2005, p. 26), it is not improbable that the Parties to the HELCOM Convention will reach agreement on an analogous procedure.

28 London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter dated 29 December 1972 and the Protocol to the London Convention dated 7 November 1996.

29 Annex 1 to the London Protocol.

30 The term »overwhelmingly« was not precisely defined, however.

Altogether, it may be noted that adaptation of treaties under international law to create legal certainty for CCS has made more headway than corresponding activities at national and EU level.

POLLUTION-CONTROLL LAW 2.3.2

CO_2-storage systems probably have to be classified at the moment as plants that are not subject to approval within the meaning of the Federal Pollution-Control Act (BImSchG).[31] Although operators of plants that do not require approval, too, must adhere to the duties to ward off dangers and protect (pursuant to secs. 22 to 25 BImSchG), no involvement of the public is envisaged here. A check should be made as to whether, in view of their hazard potential, they will have to be classified as plants that are subject to approval and be included in the implementing ordinance (Fourth Ordinance on the Implementation of the Federal Pollution-Control Act, 4. BImSchV).

WASTE-DISPOSAL LAW 2.3.3

Unenclosed gaseous CO_2 is not covered by the term »waste«, so that no permits are required under waste-disposal law. Liquefied CO_2, by contrast, may involve the application of waste-disposal law; for the supercritical aggregate state, clarification of the legal status is necessary.

The waste-disposal law contains approval instruments (plan assessment for waste-treatment plants) and substantive specifications – e.g. as regards classification, supervision of waste or the long-term safety of stored waste – which could be used to regulate CCS projects. It must be borne in mind, however, that the waste-disposal law contains no tools for resolving CCS-typical conflicts (e.g. exploration of storage sites and the rights of use emerging in the process or the clarification of the legal relationship with the land owners of the storage sites).

MINING LAW 2.3.4

The scope of the Federal Mining Act (BBergG) extends to resources »free for mining« (*bergfrei*), to those in the property of the surface owner (*grundeigen*) (incl the searching, extracting and processing of minerals (BBergG, sec. 2(1)), and to the erection and operation of underground storage facilities (incl examining the underground as to its suitability) (BBergG sec. 2(2)). The »storage« concept in the Act addresses later re-use of the stored material and seeks to demarcate this from waste disposal. However, re-using the CO_2 stored underground is not generally intended, so that mining law cannot be applied in this manner. As

31 … since they are not listed in the Annex to the 4. BImSchV.

CO_2 is not a resource within the meaning of mining law either, the Federal Mining Act in its currently valid form cannot be applied to CCS.

One fairly uncomplicated way to extend the scope of the Mining Act to CCS would be to incorporate, e.g., »*spatially delimitable rock formations that can be used for CO_2 storage in CCS*« into the Mining Act as resources free for mining, e.g. by a legal fiction[32] (this option is discussed in greater detail in Chapter VI.3.1).

WATER LAW 2.3.5

Pursuant to Germany's Water Resources Act (WHG), the deeper bodies of water (deep groundwater), too, are covered by the term »groundwater«. The storage of CO_2 both in saline aquifers and in natural-gas reservoirs would satisfy the definition of discharging substances into the groundwater (sec. 3(1), no. 5 WHG), so that this would require a permit under water law. Issuing a discharge permit under the WHG is subject to rigorous scrutiny. This covers, in particular, the explicit degradation ban (sec. 33a WHG), which is designed to ensure adherence to environmental aims (avoiding detrimental changes to the quantitative and chemical state of the groundwater).

All the same, it would be sensible to adapt the water law selectively, because at present CO_2 storage is not explicitly named in the relevant provisions serving groundwater protection. This defect could ultimately have an effect on legal certainty and impair the quality of scrutiny and supervision. What we require here are clear definitions. This applies beyond national groundwater provisions, extending to the regulations under European law as well.[33]

SOIL-PROTECTION LAW 2.3.6

Soil-protection law could apply to CCS activities. For an operator of a CO_2-capture plant, this would entail precautionary duties (under sec. 7 BBodSchG), among others. Precautionary measures can be ordered by the authorities in charge if there are concerns about harmful changes to the soil. Special attention must be paid to a precise delimitation between water- and soil-protection law since, with a legally independent protection regime being set up of for the soil, the water percolating underground has been withdrawn from the regulatory

32 In a similar manner, »geothermal energy and other energies occurring in connection with its extraction« were recently defined as a resource »free for mining« (BBergG, sec. 3(3)2.b).

33 Of relevance here are the Water Framework Directive (WFD) (Directive 2000/60/EC, OJ no. L 372/1) and the Groundwater Directive (Directive 2006/118/EC, OJ no. L 372/19).

purview of the Water-Resources Act and allocated to the Soil-Protection Act (»Soil solution« in sec. 2(1) BBodSchG).

PROCEDURAL REQUIREMENTS 2.4

According to the current state of the law, separate administrative procedures must be followed for all three CCS phases. For approval of capture, an approval procedure under pollution-control law may primarily apply. Approval of CO_2 transport depends on the type of technology employed; the construction and operation of a pipeline would be subject to a plan-assessment procedure (pursuant to the principles of secs. 20 ff. UVPG). For storage, on the other hand, an approval procedure under pollution-control law in particular, or a plan-assessment procedure under mining or waste-disposal law must be considered.

Subjecting CCS projects to an environmental-impact assessment (EIA) duty would be an option. This would be an important prerequisite for recognizing any such impact early on and for achieving a high degree of public involvement and, hence, acceptance. The present state of the law has serious gaps, however. Although the erection and operation of mining installations to extract resources that are free for mining (sec. 52(2a), sent. 1, sec. 57c, sent. 1, no. 1 BBergG) are subject to an EIA duty, the rules do not currently apply to systems for storing CO_2 underground. There is an urgent need for clarification here.[34]

LIABILITY FOR DAMAGE ASSOCIATED WITH CAPTURE, TRANSPORT AND STORAGE 2.5

When it comes to CCS, no adequate liability regulations exist at present to cover compensation for either environmental damage or personal loss or injury.

LIABILITY FOR ENVIRONMENTAL DAMAGE

The new Environmental Damage Act (USchadG)[35] has introduced the category of environmental damage into German law. This creates a damage category that is suitable in principle for covering damage to the environment from CCS technology, too, in a liability regime. All the same, the existing set of instruments does not suffice as yet to clarify all the issues arising in connection with CCS liability.

34 For the sake of clarification, the list crucial for an EIA duty in Annex 1 to the UVPG would have to be supplemented to include CCS.

35 Law on the transposition of a Directive of the European Parliament and of the Council on Environmental Liability with regard to the Prevention and Remedying of Environmental Damage (Environmental-Damage Act), Federal Gazette dated 14 May 2007, Part I, 2007, no. 19, pp. 666 ff.

There are uncertainties, inter alia, about which activities are subject to liability, about compulsory cover and about whether the 30-year statutory period of limitation is also to apply to compensation claims due to CCS technology. After all, storing CO_2 can have an impact across very long periods, so that it is questionable whether a limitation of liability to 30 years is adequate. This is all the more so, since it will not be easy to determine the exact point in time of any leakage. It is also unclear how the question is to be handled of what happens if, although the leakage occurred 30 years ago, CO_2 is still escaping.

LIABILITY FOR PERSONAL INJURY AND PHYSICAL DAMAGE

The provisions regulating liability for personal injury and physical damage, too, are inadequate at present. Germany's Environmental Liability Act (UmweltHG) in particular could be supplemented, for example. Points in need of clarification include, above all, the CCS facilities to be subsumed under the liability and the duration of the liability.

Both for ecological damage and for personal injury and physical damage, an exclusion of liability exists for damage caused by force majeure and unavoidable natural occurrences. This could turn out to be problematical, since it might be impossible to prove, e.g., whether an earthquake had natural causes or was triggered by CCS activities.

HOW TO MAKE CCS LEGALLY ADMISSIBLE? 3.

The creation of a regulatory framework for CCS is a double challenge: if we assume, on the one hand, that it is in the public interest, for the sake of climate protection, to launch CCS swiftly on an industrial scale, it will be necessary to permit initial CCS projects at short notice in order to gain experience in this technology. This experience is needed both for the further development of methods and for political and legal guidance. Several German companies already have concrete plans along these lines, some of them at an advanced stage. If the law as it stands is not amended in the short term, however, the projects in the pipeline will not be allowed.

On the other hand, a regulatory concept is needed that keeps an eye on all relevant aspects: the systematic use of scarce storage capacities; taking account of competing use claims; the creation of transparency; regional-planning challenges; integration into the climate-protection regime, etc. Such a regulatory concept would make a crucial contribution toward improving public acceptance and avoiding conflicts. However, all of this requires time – several years, as past experience has shown – for elaboration, discussion, decision-taking and implementation.

This being so, a two-stage approach may lend itself: in the course of an interim solution implemented at short notice, the legal preconditions should be created to enable projects mainly concerned with research into, and the testing of, CO_2 storage to be initiated in near real-time. At the same time, a comprehensive regulatory framework should be developed, and possibly coordinated at EU level and internationally, that accommodates all aspects of CCS technology. This could supersede the interim arrangements as soon as CCS is available for large-scale deployment.

So that industry can develop CCS technology successfully and establish it on the market, a high degree of planning and legal certainty is urgently needed. Hence, the longer-term legal framework, too, should be made predictable as soon as possible, and no system change should be made in the transition to this legal framework.

INTERIM SOLUTION TO ENABLE RESEARCH AND TRIAL PROJECTS 3.1

What follows will outline one way of creating a legal framework at short notice that permits site search and CO_2 storage for projects which mainly address research into, and the trialling of, CO_2 storage. First of all, the minimum elements in these interim arrangements are described and, secondly, reasons given – on the basis of various regulatory aspects – why such a solution will not suffice as a long-term framework for full-scale CCS. Hence, this interim framework should have a clearly defined period of validity to make clear that it will be superseded by a comprehensive CCS regulatory concept. Stressing the exceptional character is also, and in particular, necessary to avoid any long-term impairment of the creation of (regional) public acceptance.

The core element in a short-term regulatory framework would be the creation of an approval fact (*Zulassungstatbestand*) in mining law. A legal fiction could be used to place CO_2 storage sites like saline aquifers on an equal footing (as in the case of geothermal energy) with resources free for mining. This might be done, e.g., by incorporating a new no. 3 into sec. 3(3) BBergG: »*spatially delimitable rock formations that can be used for CO_2 storage in CCS*«.

Since storage of CO_2 in water-bearing rock strata must be equated with discharge of substances into the groundwater, so that it requires a *permit* under *water law*, it must be established whether existing exception permits in the EU Groundwater Directive (with, inter alia, express mention of the discharge of gas or liquid gas for storage purposes as exceptions) are applicable to the discharge of CO_2 or whether a new exemption should be created. At national level, Germany's Groundwater Ordinance gives concrete form to the handling of waterpolluting substances. However, CO_2 does not currently fall within the scope of the Ordinance. The situation may be different for any contaminants it contains whose nature and quality depend on the fuel employed. To provide the approval authorities with a basis for a decision, adapting the Groundwater Ordinance would be one workable route.

The appropriate instruments under *mining law* for the exploration and extraction of resources free for mining provide suitable tools for settling ownership and use conflicts in exploring CO_2 storage sites and in storage questions. In this respect, the mining authorizations contain, specifically, the following relevant arrangements:

- The holder of a permit has an exclusive exploration right in his area, so that he is protected from competing prospectors (sec. 7(1) BBergG).
- If a landowner refuses to allow his land to be used in the search for a suitable geological formation, the authority in charge can dispense with his consent in the public interest (sec. 40(1) BBergG).
- The authority must deny permission to explore for resources if repositories with resources may be impaired that are of special significance for the economy, so that their protection is in the public interest (sec. 11, no. 9 BBergG). This applies, e.g., to conflicts of use in exploring for and extracting natural gas. But the interest in extracting geothermal energy, too – ranking equal, by legal fiction, with a resource free for mining – would have to be weighed against an interest in exploring a CO_2 storage site.
- For reasons of investment protection, the holder of a permit for the *exploration* of resources has priority over the *use* of the resources covered by the permit (sec. 12(2) BBergG).

The approach involving the regulation of the exploration and operation of CO_2-storage sites via mining law would have a range of implications for the duty to draw up operating plans (inter alia, master, main and final operating plan), for making EIAs and for the involvement of the public.

Exploration of CO_2-storage sites (or for the search for resources) would not require a plan-assessment procedure under mining law. The consequence here would be that, e.g., no public involvement or the participation of recognized conservation associations would be envisaged in the case of exploration (cf. sec. 54(2) BBergG). Municipalities and authorities affected would merely have the right to be informed and heard by the mining authority; however the authority would not have to bring about any agreement about the decision for the operating plan, but would decide on its own responsibility (subject to the preconditions of sec. 55 BBergG). In certain circumstances, there would not even be a duty to produce an operating plan for the exploration.[36] Overall, such a procedure would hardly live up to a high standard of transparency and trust-building.

For CO_2 *storage*, the production of a master operating plan would not be mandatory in the plan-assessment procedure, since this is not listed in the catalogue of mining projects[37] with an EIA duty. However, environmental-impact assessments and public involvement are important modules for building trust in an open-ended and careful scrutiny of any project. Especially in the case of a technology about which no established level of knowledge exists as yet, this is a crucial factor, above all for regional acceptance as well. This defect could be cured by an appropriate supplement to the EIA Mining Ordinance. In such a case, the public and the recognized conservation bodies would have to be involved. Other measures, too, should be taken to ensure public involvement that go beyond the statutory minimum requirements (on this, see Chapter V »Public opinion and acceptance«).

Other authorities, like waste- or water-protection authorities, would have no co-decision rights (agreement, consent) in the approval procedure; the plan-assessment authority (i.e. the mining office in charge) would take a decision on its own, while hearing the other technical bodies. In view of the serious concerns about groundwater protection and the possible grave consequences, it is questionable whether any arrangements for approving storage are appropriate that do not provide for the agreement of the water authority.

In addition, the outlined interim solution within the scope of previous mining law harbours the risk that site exploration and use of the CO_2-storage facilities may be on a »first come, first served« basis. Although this would be acceptable for research into, and the trialling of, CCS, the result in any commercial-scale application might be a suboptimal distribution of those subterranean geological traps that can be considered for competing uses. A long-term legal framework would have to prevent this.

LONG-TERM SAFETY

To minimize long-term risks, minimum standards must be established both for the siting of the storage facility and for its operation. Guidance for possible CCS regulations as regards long-term safety evidence can be found in the analogous

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36 Wherever, e.g., only the following procedures are used: geoelectric or geochemical processes, aerial photography, seismology and activities in which only little overburden is removed for the installation of exploration equipment, and backfilling takes place straight away.

37 In the EIA Mining Ordinance.

provisions under of atomic-energy and waste law.[38] The following specifications could be considered for long-term safety evidence in CO_2 sequestration:

To investigate the overall system, some *baseline information* (taking account of site-specific and regional geological properties) should first be collected, viz. on geological and hydrogeological features (e.g. groundwater movements), storage options, reaction behaviour (solubility, interaction with other substances, impact of gas formation, migration), the influence of micro-organisms, and possible developments (erosion, earth movements, etc.). In a next step, the baseline information should be used to develop a *safety analysis using (deterministic) model calculations*, and to draw up a *safety concept*. Finally, for ultimate *evidence of long-term safety*, a comprehensive assessment appears necessary covering natural barriers, technical impact on the barriers, technical barriers, stability of cavities, migration forms and velocities of the CO_2, any harmful events and their consequences as well as a summarizing appraisal of the overall system. All investigations and calculations should be state of the art. In addition, the methodology used, the choice of scenario, the model techniques employed, the assessment standards and the conclusiveness of the data should be examined by independent experts.

Going beyond adherence to minimum standards, use of, e.g., liability-policy instruments that do justice to the leakage risk would have to be considered, so that fair competition between CCS and other emission-avoidance options (e.g. increase in energy efficiency, renewables) can be ensured.

POST-CLOSURE CARE

In the geological trapping of CO_2, the long-term safety of storage and post-closure care for the installations must be ensured in the period after the end of the operative phase as well. This must be guaranteed for the first research and trial projects already; in any full-scale use of CO_2 storage, these issues will become even more important.

The post-closure care under mining law ends either with implementation of the final operating plan (sec. 53 BBergG) or by order (sec. 71(3) BBergG). The order is issued »at the time when general experience indicates that operation is no longer expected to give rise to risks for the life and health of third parties, for other mining companies or for deposits whose protection is in the public interest, or to entail dangers to the public welfare« (sec. 69(2) BBergG).[39] In this respect, it

38 Statutory rules on long-term safety evidence, incl a definition and the criteria for producing such evidence, may be found in the so-called Underground Waste-Stowage Ordinance (Ordinance on Underground Waste Stowage (VersatzV) dated 24 July 2002, Federal Gazette I, 2002, p. 2833).

39 How this provision can be applied to CCS projects is questionable since no »general experience« exists (yet).

must be noted that mining supervision, once it has ended, is not revived if subsequent hazards arise (Boldt/Weller, Bundesberggesetz (Federal Mining Act), sec. 69, marginal note 19). Any post-closure care pursuant to waste law could only be considered if CO_2-storage sites were deemed to be waste-disposal plants (sec. 36 KrW-/AbfG).

One of the biggest legal uncertainties concerns the question of who is to monitor the long-term operating safety of the storage sites, which authorities are to supervise such monitoring, and who is to bear the costs (WD 2006, p. 30).

FUNDAMENTALS OF A LONG-TERM REGULATORY FRAMEWORK FOR CCS 3.2

For implementing a CCS law in legislative-technical terms, various routes are open. First, a new special statute (»CCS Act«) could be created for comprehensive regulation of CCS. Also feasible, second, would be an adaptation of the various existing special statutes affected, viz. by a composite act (*Artikelgesetz*). A third option could be integration into the Environmental Code (UGB) currently being prepared whose first parts are to be adopted by the end of the present legislative term. Each of these options has its specific sweet spots and weak spots as regards legislative procedure and content.

One point in favour of integration into the UGB is that this could counteract a further splintering of environmental law. Another argument in favour is that the high integration requirements of any CCS regulation could benefit in particular from the UGB's holistic concept. One objection to inclusion in the UGB is that this would complicate even more the creation of an environmental code. Due to the multitude of open issues, rapid progress in CCS legislation could also be hindered, all the more so since the only projects to be governed by the UGB are those that will be entirely regulated under the auspices of the Federal Environment Ministry (BMU).

The answer to the question of whether a stand-alone CCS law or a composite act makes more sense depends on whether CCS is regarded as a separate regulatory field, which would then stand on its own alongside previous law, or as a cross-section issue. In the latter case, amalgamation and harmonization of new and old regulations in one composite act might be the more effective route.[40] On the other hand, a composite act would mean amending a large number of existing statutes, since each of the three elements – capture, transport and storage – would have to be located in different special statutes. Having to take account of

40 One question regarded as a cross-section issue, for example, is the high-water problem, which has found a statutory solution in a supplement to water and urban-planning legislation.

demarcation issues between various legal fields and regulations would contribute to the complexity of a composite act. This is especially true of the procedure for competing uses and regional-planning questions in the case of CO_2 capture and storage.

The creation of a uniform CCS statute would have the merit that all rules would be regulated in context and the law would be of-a-piece. For public acceptance and transparency, this would be an advantage. Better account could be taken of the interdependence of the three elements – capture, transport and storage – in a CCS statute. For overarching issues (e.g. emissions trading), too, an integrated view would have its merits, although this would require a high degree of coordination and far-sightedness.

When account has to be taken of underlying political conditions and the legislative procedure, heed must be paid in Germany to the influence of the federal states, which has grown in some areas with the reform of the federal structure.[41] Still, this applies to any option for implementing a statute.

FUNDAMENTAL ELEMENTS IN A CCS LAW

Irrespective of which of the above regulatory options is preferred, the regulatory requirements can best be debated using the example of a CCS statute. So what follows puts up for discussion a proposal for the fundamental elements of a CCS law. It was produced within the scope of the TAB project by Öko-Institut (Öko-Institut 2007) and briefly debated at an expert workshop on 18 January 2006 by representatives from science, industry and environmental associations.

Provided that long-term CO_2 storage in geological traps proves technically doable, so that CCS can stand as one option for climate mitigation, a CCS statute would have to do justice to the following requirements and objectives:

- Establishing the fact that long-term, safe storage of CO_2 is in the public interest.
- Identification of the sequestration processes said to be suitable in principle, the regions suitable for this purpose and, possibly, specific sites under a nationwide plan for CO_2 storage (»CCS plan«).
- Creation of an integrated licensing process (ILP) with public involvement for licensing concrete CCS projects.
- Definition of basic requirements to be met by capture, transport and storage, in order to take precautions against risks to health and the environment (incl suitable monitoring procedures).

41 A detailed discussion of regulatory authority at national and state level may be found in Öko-Institut (2007, pp. 83 ff. and 90 ff.) (in German).

- Regulation of the liability for third-party personal injury and physical damage and for environmental damage not related to climate protection.
- Provision for the way storage is to count toward CO_2 trade in emissions.

Three core elements of the proposal, viz. the nationwide CCS plan, the ILP and the regulation of liability for damage, are discussed in more detail in what follows.

The purpose of the CCS plan to be drawn up by the Federal Government is to give CCS projects an edge over competing uses. To this end, regions or specific sites whose geological properties have been shown to be particularly suitable for CO_2 storage are identified as CCS »priority areas«. Also, certain simple use areas (*einfache Nutzungsgebiete*) may be defined as being suitable in principle for CO_2 storage.[42] The foundation for this would be a robust data base (»CO_2 land register«) which would depend on the findings of systematic underground exploration. In principle, exploration could be undertaken by the private sector or else viewed as a public remit. One advantage of the latter option is that the findings would be fully available for public bodies in the approval procedure, for other public interests and for later monitoring tasks. This solution would also be in line with the assumption that CCS is in the public interest and avoid a situation where investment risks for the private sector have an inhibiting effect on a swift scrutiny of specific sites. One institution suitable for this would be, e.g., the Federal Institute for Geosciences and Natural Resources (BGR). As specification for the number and size of the priority areas, it is worth considering whether setting a national quantity target for CO_2 storage would be meaningful.

The second core element in the proposed regulation is the introduction of an ILP for CCS, i.e. a joint approval procedure for all three project stages (capture, transport, storage). Its final shape would be that of a plan-assessment procedure with a concentrating effect (*Konzentrationswirkung*). The plan-assessment ruling would then involve, inter alia, the issue of three partial approvals for operation of the capture system, for any pipelines, and for storage proper. On the upside, such an approach could integrate all specialist authorities affected (pollution control, mining, water, soil protection, traffic, spatial planning).

The main argument for having three separate procedures is that CO_2 capture, transport and storage are events that can be separated technically and in time. In fact, proven approval procedures could be drawn on for capture and transport, so that only one new procedure would have to be developed for CO_2 storage (DEBRIV 2007). One drawback would be that full account would not be taken of the interdependencies of the three procedures. For instance, when a capture system is being approved, say, no check would be made as to whether transport

42 One analogy would be, e.g., Germany's Federal Transport Infrastructure Plan (BVWP) with its classifications »urgent« and »other« requirements.

routes and storage capacities are available on the required scale. In an extreme case, this could mean that a power plant might be approved and built that has efficiency losses compared with a power station without capture, but where no actual storage of the captured CO_2 takes place.

Whether the procedural outlays would ultimately be higher for an integrated process or for three separate procedures cannot be finally assessed here. On the one hand, an integrated process would require that a complex technology field be examined and approved in its entirety. On the other, decision-relevant approval facts would only have to be assessed once, which might yield a reduction in procedural outlays. Separate procedures would have the disadvantage that considerable expense would be needed for coordination between the technical authorities involved.

The rules for liability issues are of great importance. Here, a dilemma must be resolved: according to the polluter-pays principle, operators are responsible for all damage and loss originating in storage facilities. However, if the arrangements adopted hold operators liable without limitation for long-term damage as well, the outlays for compulsory insurance cover might be so prohibitive that it is no longer possible on economic grounds to exploit the potentials of CCS for climate mitigation. On the other hand, less rigorous rules would shift the risks or costs on to the public purse. Among other things, this could distort the competition between CCS and other low-CO_2 power-generation technologies and weaken public acceptance of CCS (ACCSEPT 2006).

In view of the long-term nature of CO_2 storage, a shift of liability from private operator to state is probably inevitable after a certain time and under certain circumstances. Both the Environmental Damage Act (USchadG) and the absolute offence (*Gefährdungstatbestände*) in civil liability (limitation of claim) specify a maximum period of 30 years. The question must be examined in depth as to whether CCS liability needs a longer timeframe. Differences could occur when considering personal loss or injury and environmental damage. A longer period may well be necessary for environmental damage.

To rule out a situation where, due to a change of operator or possible insolvencies, the general public (ands coming generations) has to foot the bill for damage to humans and the environment caused by escaping CO_2 during the period of liability of the author, the issue of adequate compulsory cover for the stored CO_2 must be discussed.

Liability rules for the cross-border disposal of CO_2 and storage in international sovereign territory must be laid down in international treaties (e.g. London Convention/Protocol and OSPAR). Here, it must also be clarified whether the CO_2 emitter or the country of origin would be responsible.

HOW TO MAKE CCS ECONOMICALLY ATTRACTIVE? 4.

One central issue is that of the incentive mechanisms that can be used or created to make CCS an attractive proposition, also in the eyes of private investors, so that it can come to bear in the energy system as well. For this, we must, on the one hand, analyse, at the level of the international climate-protection regime, how advantages can emerge from CCS technology for the participating states. On the other, the question must be asked as to the regulatory approaches that could induce investors in Germany or in the EU to implement CCS. Between the two levels – mainly in the area of the so-called flexible instruments of the Kyoto Protocol and the EU Emissions-Trading Scheme (ETS) – there is close interaction, although it is useful to start by analysing the two levels separately. The assumption here is that the CCS technology chain appears practicable in demonstration projects at least, and that commercial availability is at least foreseeable.

FRAMEWORK CONVENTION ON CLIMATE CHANGE AND KYOTO PROTOCOL 4.1

The Framework Convention on Climate Change (FCCC) and the Kyoto Protocol are the cornerstones of international efforts on behalf of climate mitigation. Hence, CCS can make a contribution only if CO_2 capture and storage is recognized in these treaties under international law as CO_2 emission reductions.

For the participating industrialized and transition countries (so-called »Annex I states«), the Kyoto Protocol sets caps for their CO_2 emissions (so-called »Assigned Amount Units«, AAUs) in the first commitment period (2008-2012). AAU certificates are tradable in International Emissions Trading. In addition, the states can generate emission-reduction certificates from the so-called project-based mechanisms: »Joint Implementation« (JI, between the various Annex I states) or the »Clean-Development Mechanism« (CDM, between industrial states in Annex I and developing countries). These can then be used together with the AAUs as evidence of adherence to the commitments entered into under the Kyoto Protocol. Both in defining reduction targets and in checking that commitments are met, the states must draw up national greenhouse-gas inventories that are drafted on the basis of unitary guidelines and subjected to a complex verification process.

Within the purview of the Kyoto Protocol (and of the FCCC), therefore, the following questions arise:

- How is CCS taken into account in the greenhouse-gas inventories (reporting)?
- How is CCS valued as evidence of commitments being met (accounting)?
- How is CCS treated in the flexible mechanisms of the Kyoto Protocol?

The integration of CCS into the Kyoto Protocol becomes especially difficult if CO_2 capture and storage is in different countries:

- The situation is simplest if both the country doing the separation and the country doing the storage are subject to quantitative emission targets.
- Not uncomplicated is the case where both countries have ratified the Kyoto Protocol, but only one has given an undertaking on quantified emission targets.
- It becomes very complicated if one of the two countries has not ratified the Kyoto Protocol (i.e. creating a similar set of problems as for emissions trading in international air traffic).
- For all three cases (pragmatic) solutions are conceivable; at any event, the specific CCS problems will result in a need for international negotiations in the broad-deployment phase at the latest.

Pursuant to the definition made by the FCCC of key terms, like »emission«, »emission source«, »sink«, storage facility (»reservoir«), CCS can only be taken into consideration via *emissions avoided*.[43] In practice, this means that

- only the residual emissions are inventoried for the place of capture and taken into consideration for meeting commitments;
- any emissions from the downstream system in the CCS process chain (mainly leakages) must be established separately and inventoried.

In its recently revised guidelines, the IPCC has set out rules for CCS which for the first time describe the method and procedure for recording the CO_2 emissions of the CCS process chain in the national inventory (IPCC 2006). The rules require that emissions from power stations be calculated on a plant-specific basis (measurements in the flue-gas stream). Any emissions in CO_2 pipeline transport are calculated using standard emission factors known from natural-gas transport and converted for CO_2 transport. In CO_2 injection into storage sites, measurements of flow rate, temperature and pressure at the drill hole are envisaged to determine the stored amount. For emissions from the storage facility (leakage), no emission factors can be determined to date for lack of empirical data. This being so, the IPCC provides for a methodology to estimate the emissions based on a closely meshed monitoring programme specifically tailored to each and

43 Science is also discussing taking account of sinks (e.g. Bode/Jung 2004). These are not further thematized here.

every project. It is important to ensure consistency of the reported inventories and verifiability of data here.

Accepted methods for taking CCS into consideration within the scope of the flexible instruments of the Kyoto Protocol (JI and CDM) do not exist at present due to the multitude of unclear political, legal, technical and methodological issues. This subject is discussed in greater detail in Öko-Institut (2007, pp. 116 ff.) (in German).

INCENTIVE FRAMEWORK IN THE CONTEXT OF GERMANY AND THE EU 4.2

Taking CCS into consideration in the international climate-protection regime would ensure that the participating states have an incentive to have CCS deployed in their sphere of influence. This does not by itself mean that economic agents are likewise incentivized to use the technology. Separate instruments are necessary for this. The following, fundamental approaches to national and EU-wide policies and measures may be distinguished:

- the ETS closely interlocked with the international climate-protection regime of the Kyoto Protocol;
- further specific, political instruments with which CCS can be promoted, above all in the demonstration and early market-penetration phase;
- the options for enforcing CCS by taking the regulatory-law route for new and, possibly, existing plants as well;
- other potential tools designed to create incentives for the development of the safest possible storage sites.

What follows will detail and discuss these approaches in their various dimensions.

EU EMISSIONS-TRADING SCHEME 4.2.1

Use of the ETS as a tool for pricing CO_2 could without doubt create a crucial precondition for the economic attractiveness of CCS technology. Under the ETS, plant operators are provided with emission certificates, so-called »European Union Allowances« (EUAs), which are directly linked to the emission permits of the Kyoto Protocol (AAUs) allocated to states under the terms of the Protocol. Thus, the EU states, via the ETS, are *de facto* »privatizing« the international emission permits allocated to them as states.

RECORDING

Under the previous demarcation, the plants that capture CO_2 would fall within the scope of the ETS, but not the emissions that emerge in the further stages along the CCS process chain (transport, injection, storage). This would be true both of direct (»fugitive«) emissions (e.g. from leaks) and of associated emissions, e.g. due to the energy requirements for compression, liquefaction, etc. Since this would undermine the ETS's integrity, there is an urgent need for revision and amendment. Above all the recording of fugitive CO_2 emissions would enter unknown territory.

The EU Emissions Allowance Trading Directive[44] would either have to be amended to have all installations in the downstream process chain covered by the ETS for energy-related CO_2 emissions (mainly compressor drives) and fugitive emissions for the normal operating and the disruption situation. By way of alternative or as a pragmatic interim step, an approach harmonized between the Member States concerned could be pursued for the »opt-in« of CCS installations.[45]

REPORTING

The crucial provisions for the treatment of CCS installations under the ETS are those governing the production of emission reports. The previously applicable rules contain no binding rules for CCS. The UK in the meantime has assumed a pioneering role and drafted monitoring and reporting guidelines for CCS projects in Britain (DTI 2005). It is worth stressing that these do not recommend that emissions from any CO_2 leaks from the storage sites be included in the ETS, but that problems of this kind be treated entirely in the approval procedures concerned, thus underpinning the ecological integrity of CCS in the ETS.

Ultimately, the way the various technologies in the CCS process chain are incorporated into the ETS will depend on the IPCC's methods and on the Member States' experience gained in pilot and demonstration projects. Against this backdrop, it is recommended that the production of contributions to the development of reporting guidelines be explicitly included in the programme for the demonstration and pilot projects now being started.

One specific problem arises from the currently debated special regulations under the ETS for small emitters. To ease the burden for the operators of small installations, discussion is mainly centring on special allocation arrangements or on

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44 EU Directive 2003/87/EC establishing a scheme for greenhouse-gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

45 Pursuant to Article 24(1) of the EU Emissions Allowance Trading Directive, Member States may also subject installations to the ETS that are not included in the list of installations mandatorily covered by emissions trading (opt-in).

lower monitoring requirements. In view of the currently discussed threshold values for such special arrangements (20,000 to 50,000 t CO_2/yr), it follows that medium-sized power plants with CO_2 separation could be affected[46], which would certainly not reflect the original intention of these special arrangements.

ALLOCATION AND EMISSION TARGETS

Inclusion of CCS process-chain systems in the ETS and the establishment of guidelines for emission reports would merely create the prerequisites for also monetizing the CO_2-emission advantages of CCS relative to competing plants. As regards the scale of the economic advantage, the allocation of the emission permits has a central role to play.

At present, pursuant to the EU Emissions Allowance Trading Directive, *at least* 95 % of the emission permits to be issued must be allocated to the installations free of charge; for the period 2008-2012, the amount falls to 90 %. To what extent the share of emission permits that are *no* longer allocated free of charge will rise perceptibly in the periods after 2012 cannot be foreseen at the moment.

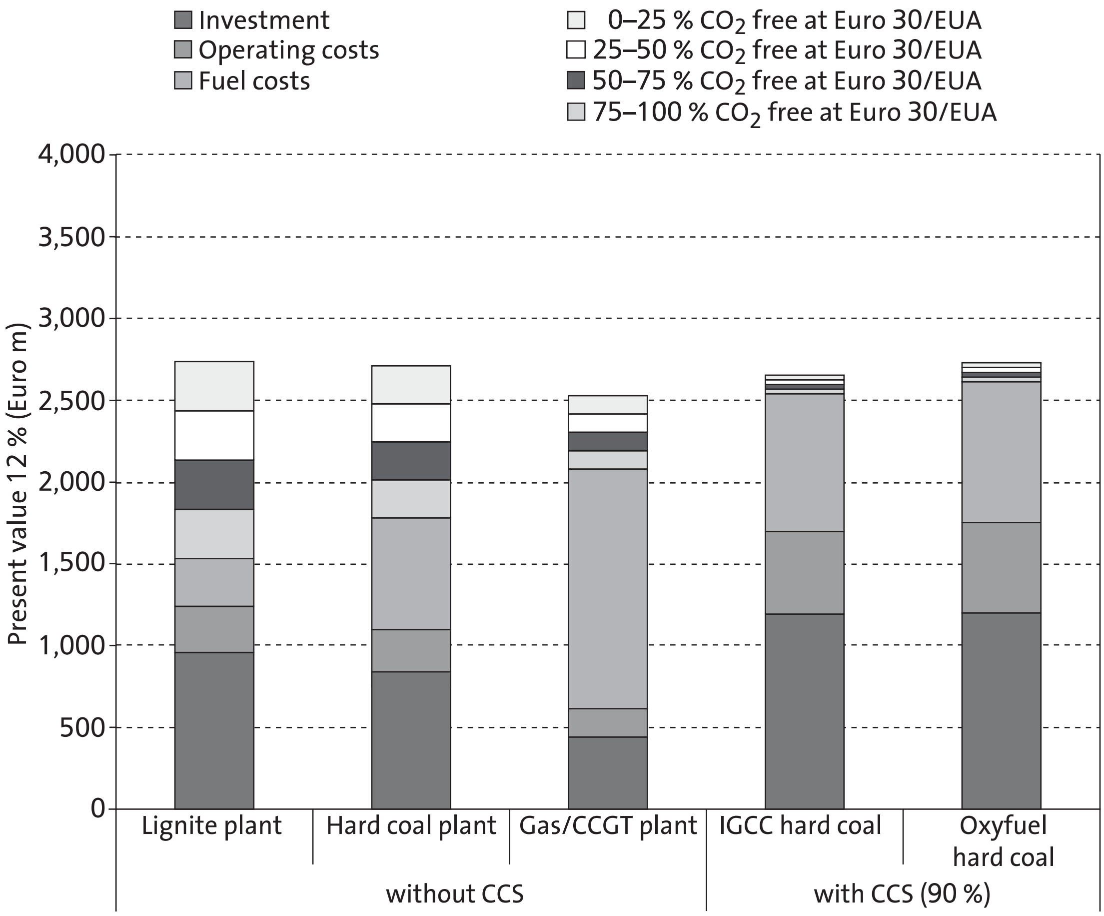
Although it is true that the allocation of emission permits is of only subordinate importance for the economic efficiency of *plant operations* (e.g. Matthes *et al.* 2005), the situation is completely different when it comes to *investment decisions* for CCS that compete with other investment options. If larger numbers are allocated free of charge, depending on an installation's emission level, the economic benefits for CCS investment due to the lower CO_2 emissions erode massively.[47]

Figures 20 and 21 highlight the connection between free (and fuel-differentiated) allocation to new installations and the economic attractiveness of CCS investment (for assumptions and calculation methods, see Öko-Institut [2007, pp. 128 ff.] in German). The so-called present value shown in the Figures enables a direct comparison to be made between various investment options.

46 A power plant with a net output of 300 MW and annual capacity utilization of 6,500 hours with an efficiency (after capture) of 35 % and a capture rate of 99 % would release just under 20,000 t CO_2 into the atmosphere per annum.

47 If investors in new installations can expect that, in an extreme case, they will be allocated the emission permits needed to operate the plant completely free of charge and, depending on their plant's emission levels, largely »as required« (i.e., e.g., via fuel-specific benchmarks on the basis of the best-available technology), they will decide as if there were no trade in emissions (the present value of the certificates to be handed over is equal to the present value of the certificates allocated for free). This being so, when the present value is calculated, a CCS system loses all of its edge in operating costs (on this, cf. Matthes *et al.* 2006).

FIG. 20 PRESENT VALUE OF VARIOUS INVESTMENT OPTIONS (WITH AND WITHOUT CCS) AT A CERTIFICATE PRICE OF EURO 30/EUA

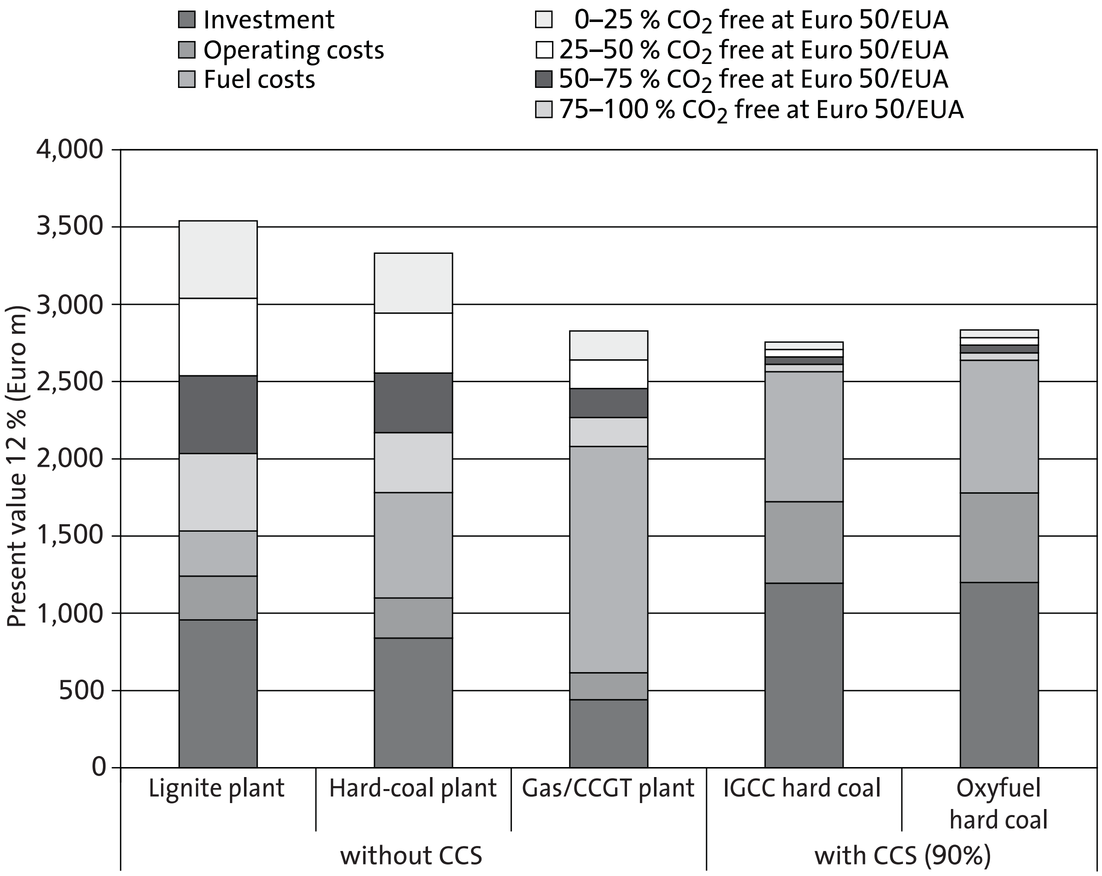


Source: Öko-Institut 2007

At a certificate price of Euro 30/EUA (Fig. 20) and assuming allocation of emission certificates completely free of charge, CCS power plants would be much more expensive than the options without CCS. The least-cost power-generation option would be lignite, followed by hard coal and natural gas. Only when free allocation is less than about 10 % of their needs, does investment in CCS power plants prove increasingly attractive. At a certificate price of Euro 50 (Fig. 21), free allocation of about 25 to 35 % of the certificates needed leads to a disadvantage for CCS compared with the various investment options.

The result of these calculations, cited here as example, means that investment in CCS is not attractive wherever newly built conventional power plants can reckon with receiving a significant number of the required emission rights free of charge. If certificate prices were low and/or fuel prices high, this would further aggravate the situation.

FIG. 21 **PRESENT VALUE OF VARIOUS INVESTMENT OPTIONS (WITH AND WITHOUT CCS) AT A CERTIFICATE PRICE OF EURO 50/EUA**



Source: Öko-Institut 2007

As a consequence, further development of the ETS *requires far-reaching changes* if CCS is to be established as a competitive technology – even given massive improvements in the technical and economic parameters:

- The emission-reduction targets (caps) must be set so as to yield a certificate-price level that is (well) above the Euro 30/EUA mark.
- The free (and fuel-dependent) allocation for competing new installations without CCS would have to be replaced by auctioning of the emission permits.

In view of the now upcoming revision of the EU Emissions Allowance Trade Directive for the period until at least 2018, appropriate amendments would have to be included in the current review process already.

OTHER PROMOTION INSTRUMENTS 4.2.2

MARKET LAUNCH AND DIFFUSION

At least for the introduction and diffusion phase of CCS, it could be sensible to use specific instruments for the market launch. Such instruments have been used in the past for various technologies and form part of the established toolbox alongside the relevant R&D programmes:

- Both for nuclear-power stations and renewable energies (here mainly wind and solar), special programmes have been used in the past in which *investment* was directly subsidized or the *financing of the investment* included *state aid* (250-MW Wind Programme, 100,000 Roofs Photovoltaic Programme, interest subsidies for investment in nuclear energy).
- For the first larger demonstration nuclear-power stations in Germany, *risk-sharing measures* have been taken on a substantial scale that allowed energy utilities to be released from the additional operating risks involved in the investment concerned.
- Germany's Renewable-Energy Sources Act (EEG) guarantees the purchase of electricity generated from renewables and pays *guaranteed* feed-in *prices* that are allocated to the final buyers of electricity.[48]
- Under the country's Combined Heat and Power Act (KWKG), a defined *mark-up* is paid for the feed-in of CHP electricity, with marketing of the power usually remaining with the producers. Here again, there is an allocation to the final consumer, though without any duty to purchase the subsidized CHP electricity.[49]

In principle, corresponding instruments could also be deployed for the launch of CCS (although this does not necessarily mean that the funding concerned is available in every case):

- Creation of an investment-allowance programme or the grant of financing allowances for the first CCS plants. Such allowances can only be granted within the scope of the EU's aid-scheme rules and would require justification.
- Risk-sharing measures could be taken to promote large-scale demonstration projects to the extent that the state assumes the risk for any unplannable operating problems at CCS plants. These instruments, too, would have to be admissible under the EU's aid-scheme regime or require approval accordingly.

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48 Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, EEG) dated 21 July 2004 (Federal Gazette I, p. 1918), most recently amended by Article 1 of the Act dated 7 November 2006 (Federal Gazette I, p. 2550).

49 Act on the Sustainment, Modernization and Development of Combined Heat and Power Generation (Combined Heat and Power Act, KWKG) dated 19 March 2002 (Federal Gazette I, p. 1092), most recently amended by Article 170 of the Ordinance dated 31 October 2006 (Federal Gazette I, p. 2407).

- For a transition period, the zero-emission share in the power generation from CCS plants could be included in the subsidy regime under the EEG. This promotion approach would not be subject to the EU's aid-scheme rules, since no public funds would be involved.
- By analogy with the KWKG, the feed-in of zero-emission electricity from CCS plants could be promoted by paying a mark-up for a transition period; marketing the electricity would not be subject to additional regulation.

How and in what combination suitable promotion tools can be finally shaped for the launch of CCS will only be discussed in greater detail when more extensive investment is made in demonstration plants or when broader commercialization of CCS is upcoming. Irrespective of this, further analyses and preliminary work, e.g. on the required level of funding, on issues under the law governing grants, on the efficiency of funding and on public acceptance of the various approaches to funding, are useful.

REGULATORY REQUIREMENTS FOR THE USE OF CCS

Beyond the route of a market-driven dissemination of the CCS technology (possibly after a launch phase with specific promotion instruments) pursued above all by the ETS, market penetration of CCS technology driven by regulatory law is also being discussed. Thinking along these lines has come, e.g., from the EU Commission (EU Commission 2007b) and the British parliament (House of Commons 2006).

For *new plants*, this is relatively easy under existing rules: threshold values for CO_2 emissions (in regular operations, possibly differentiated by plant capacity and fuels) could be introduced, similar to those in place hitherto for classic pollutants within the scope of the Ordinance on Large Combustion Installations (GFVAO). If the threshold values are sufficiently rigorous, CCS as a technology could prevail. Such a threshold value could either be stipulated as a fixed value (e.g. 100 g CO_2/kWh) and/or as a minimum rate for CO_2 capture[50].

The situation for *retrofits with CCS technology* is more complicated. Although there have in the past been general retrofit duties in Germany with a high degree of interference in the area of threshold-value specifications for legacy plants in the case of sulphur dioxide and nitrogen oxides.[51] Whether such an approach involving very costly retrofitting with CO_2-capture systems would be feasible requires further analysis. In this context, the question would also have to be ex-

50 By analogy with the development targets of the DoE (2006), this target value could be geared to 90 %, for example.

51 13th Ordinance on the Federal Pollution Control Act (Ordinance on Large Combustion Installations) dated 14 June 1983 (Federal Gazette 1983 I, no. 26, pp. 719-730). In the period from 1982 to 1990, this necessitated investment in retrofits worth approx. DM 20bn.

amined of the extent to which a time limit – not customary, at least hitherto, in German pollution-control law – for permits could form a suitable approach. One other possible step in principle would involve a suitable requirement or requirement proviso to restrict the protection of the status quo in an installation without capture in such a way that retrofitting is mandatory as soon as the technology is available on a commercial scale.

The fact is that the implementation of such provisions could encounter legal hurdles due to the high investment and the inability to predict exactly when the technology will be available. Legal certainty in such incidental provisions for the pollution-control authorities in charge and for the operators – if this approach is to be pursued – could be created or improved by introducing an appropriate explicit legal basis.

As an interim solution pending commercial availability of the CCS technology there is talk of a duty to adhere to the capture-ready criteria in erecting new plants (EU Commission 2007b; G8 2005, item 14c). Discussion of such criteria has only just started; so far, the following elements for capture-ready specifications have been debated (EPPSA 2006):

> taking account of space requirements in planning and building the installations;
> taking account of the compatibility requirements of the power-plant systems and components for the new process parameters that retrofitting entails;
> choice of site and spatial link-up to future storage facilities or the infrastructure for CO_2 transport;
> adherence to the safety requirements in the power plant for any future use of the chemicals required for CO_2 capture.

Adherence to these requirements could – despite all the uncertainties attaching to future technology developments – be included in the approval procedure for new power plants to be built by way of appropriate advance planning (Gibbins 2006). At any event, the introduction of capture-ready requirements still needs in-depth, further analyses before they could be legally codified. In this respect, the growing discussion about the economic dimensions of capture-ready requirements should also be borne in mind, e.g. the build-up of financial provisions for the retrofitting with CO_2-capture systems or the purchase of options on transport and storage capacities.

OTHER INSTRUMENTS FOR MITIGATING LONG-TERM RISKS

With a view to mitigating long-term risks, incentives should be created to ensure that the safest possible storage sites are chosen and given preference. This aim can be pursued, firstly, by using tried-and-tested instruments, i.e. evidence and approval requirements for storage systems, and via the arrangements governing liability for any damage. Unconventional tools may also be candidates. Here, a number of proposals have been submitted that mainly addressed the possibilities available for integrating CCS into the international climate-protection regime (Bode/Jung 2004 and 2005; OECD/IEA 2004b). Held *et al.* (2006), by contrast, suggest a bond system which aims, indirectly at best, at inclusion in the current international climate-mitigation regime. Plant operators who store CO_2 have a duty, depending on the amount of stored CO_2, to acquire *bonds* issued by the state which are bought back at the end of their term, but are freely tradable in the meantime:

- In a first variant, a bond must be purchased per tonne of CO_2 at a price fixed by the state, the bond bearing interest during its term. If, during the term of the bond (roughly 30 years), the storage site develops leaks, the bond is correspondingly devalued or expires (the corresponding funds would then be available to the state to finance other climate-mitigation measures). If no leaks are detected, the bond is taken back at the end of its term at the issue price.
- In a second variant, »quasi-emission permits« are issued for the stored CO_2 amounts that differ from regular emission permits in that they cannot be used until released by the authority. This release is not made until the safety of a storage site has been sufficiently evidenced, or only for that part of the emissions that are shown not to have been discharged into the atmosphere again via leaks. The precondition for this variant, however, is that operators of systems with CO_2 capture would initially have to purchase regular emission permits under the ETS on a scale as if the CO_2 had not been captured and handed over to the storage facility.[52]

Both variants have the advantage that, beyond the approval procedures, an incentive system is created which develops only the safest deposition sites in the light of current knowledge. The chief disadvantage is that, specifically for companies' investment decisions, additional costs are incurred that burden CCS investment compared with other options.

Even if the proposals presented so far for creating incentive systems via environmental bonds are still marked by a range of problems, further analyses in such innovative approaches to the steering of events make sense.

52 This approach would lend itself especially well for following on from the variant in which CO2 storage would be considered not as reduced emission, but as sink extension.

NEED FOR ACTION VII.

The following discussion of the need for action in the promotion and accelerated development and use of CO_2 capture and storage (CCS) assumes a public interest in implementing CCS. A public interest could exist above all wherever the use of CCS would be viewed as a realistic and future-capable option for reaching ambitious climate-protection targets.

In the light of today's knowledge, as outlined in the above Chapters, and before the technical and economic feasibility of safe geological CO_2 storage is proven, this assessment is necessarily marked with uncertainties. Hence, systematic efforts should be made to broaden the knowledge base and close critical knowledge gaps in order to place the appraisal of the potentials and risks in CCS technology on a sounder foundation.

At the same time, however, there are some considerable time pressures at work, so that we should not gamble away the potential contributions CCS can make to achieving global CO_2 reduction targets. On the one hand, the renewal of the German (and the European) power-plant fleets will be picking up speed in the next few years. On the other, enormous dynamism can be observed in countries like India and China as they expand their fossil-fired power-station capacities, so that the window of opportunity for CCS technology to benefit the climate becomes narrower and narrower, the later it is available on the power-plant market.

Hence – alongside closing knowledge gaps and promoting the further development of the CCS technology – there are two central fields of action for public funding in the TAB's view: firstly, it is necessary to intensify the existing discussion process among stakeholders (companies, science, environmental associations, policymakers), and to initiate a public debate to sound out conditions and possible routes toward public acceptance of CCS technology. As past examples show (e.g. genetic engineering), any omissions and mistakes in informing and involving the public made at the start of a technological development are difficult to correct at a later stage.

Secondly, there is immediate and urgent need for legislative action to create an adequate regulatory framework. This would have to achieve three essential objectives: (1) ensuring the legal admissibility of CCS, (2) clarifying the handling of CCS risks and liability for any damage, and (3) creating incentives so that CCS is in fact used in practice.

BROADENING THE KNOWLEDGE BASE – CLOSING CRITICAL KNOWLEDGE GAPS

The present state of our knowledge and the need for research in the three essential links in the CCS technology chain – CO_2 capture, transport and deposition – show great variations. CO_2 storage and the associated geoscientific issues in particular require an improved knowledge base. Numerous critical knowledge gaps must be closed prior to any robust assessment of the technical and economic feasibility of CCS and an appraisal of what contribution CCS can make to achieving climate-protection targets.

Where research and development in the area of *CO_2 capture* concerns the further development of established technologies, industry (power-station and plant engineering, energy utilities, chemical industry) is called upon to act as primary operator. The main remit for state players here would be to shape the research-, energy- and climate-policy framework in such a way that companies find a dependable environment within which the socially desired research initiative can unfold in full.

Prime candidates as fields of action for the public funding of research would be highly innovative processes with great potential ecological and macro-economic benefit. If these were to be developed by companies on their own, the risk of failure would be very high (e.g. the ZECA process). In addition, the promotion of cross-section fields (e.g. material research on membranes) lends itself for obtaining synergies and generating benefits across sectors.

Likewise, the further development of technologies for *CO_2 conditioning and transport* is a task for which industry would be predestined. However, since use of CO_2 storage on a large scale would require the erection of a suitable (mainly pipeline) infrastructure, government would play an important role in its planning and design, and in optimizing any CO_2 network that may have to be built up.

As mentioned at the start, the biggest knowledge deficit and the most extensive need for research exist in *CO_2 storage*. Also, it is in broadening this knowledge base that the state is particularly called upon to act. By contrast, when it comes to exploring specific sites and to investigations that come directly before CO_2 storage, it is primarily private investors that have a part to play. Issues that would be particularly good candidates for public promotion would include, above all:

- broadening our basic knowledge of the interaction between injected CO_2 and the material of the storage formations and the caprock;
- the most exact possible determination of capacities, and studies of geological traps as to their suitability for permanent CO_2 storage. To gain precise data,

detailed investigations of formations on a case-by-case basis are indispensable;
- in the area of any competing usage rights, there is an urgent need for research, which should be tackled at once. This also includes the question of how conflicts of use would have to be resolved (e.g. priority rules).

For any robust assessment both of the potentials of CO_2 storage and of possible risks to humans, the environment and the climate, it is essential that experience is gained in CO_2 storage on a scale running into millions of tonnes. In addition to careful selection of a site, such projects should be accompanied by a rigorous monitoring programme to help better understand the processes occurring in the rock, and to reliably predict the future behaviour of CO_2 in geological formations.

Going beyond the continuation of the individual technologies that currently work on a pilot scale, one crucial challenge at the moment is their integration into an overall system on a plant scale that is relevant for power stations. It is difficult to imagine how such demonstration plants could get by without public funding. This is also the thrust of the EU Commission's proposals in this connection for promoting the construction of ten to 12 large demonstration systems by 2015. It might be worth considering going along proactively with this process at EU level and supporting it by taking national measures.

One urgent recommendation would involve integrating concomitant social- and environmental-science research into the implementation of these projects at an early stage, so that the development of the technology can be geared to the criteria of sustainable development, and so that knowledge of the economic, ecological and social consequences of CCS is made available for decision-takers. This includes an analysis of potentials, risks and costs, lifecycle considerations and issues of integrating CCS into the energy system.

CCS technology could unfold its greatest benefit above all if it were employed swiftly on a global scale. Hence, thinking is necessary on how this can be promoted by international cooperation in research and technological development, by encouragement of an international dialogue and support for capacity building, and by technology transfer to the relevant newly industrialized countries (e.g. China, India).

TRIGGERING A PUBLIC DEBATE AND DEVELOPING PUBLIC ACCEPTANCE

Although the CCS debate in specialist circles has grown significantly in intensity and dynamism of late, the subject has hardly reached general public awareness as yet. The state of knowledge of the subject in the population – as established by surveys – is still meagre. To avoid lack of acceptance inhibiting further development and use of CCS technology, a nationwide strategy of communication, information and consultation should be drafted and implemented in good time. This process should be structured so as to leave the outcome open and to sound out whether and how the broadest possible social consensus could be achieved. This is a demanding task which should be started before the first concrete siting decisions have to be made.

One possible first step in organizing this communication process involves setting up a national »CCS forum«. At present, the number of stakeholders actively engaged in the debate about CCS at national level is fairly small, so that it should be possible to bring together all relevant opinions in an approx. 20-strong forum. Besides defining the precise distribution of roles and jurisdictions, a first issue to be clarified would be who could act as the initiator or organizer of such a forum. Since neutrality is crucial for the credibility and success of such a body, future operators of/applicants for CCS plants would not make ideal initiators. Possible candidates, would be, e.g., the BMU (or the UBA), the Forum of Future Energies, the COORETEC advisory board or the German Council for Sustainable Development. It would certainly help if a well-known personality with a positive public impact could be won over to chair the forum.

CREATING A REGULATORY FRAMEWORK

In Germany, several companies are already planning concrete CCS projects, some of which are at an advanced stage. The planned projects are inadmissible, however, if current law is not adapted at an early date, so that there is urgent need for action here.

A two-step procedure lends itself: in the course of an interim solution to be implemented at short notice, the legal prerequisites should be created so that projects mainly concerned with the research into, and the trialling of, CO_2 storage can be launched in near real-time. The core element of a short-term regulatory framework would be the creation of an approval rule (*Zulassungstatbestand*) in mining law.

At the same time, a comprehensive regulatory framework should be developed and if possible coordinated at EU level and internationally to accommodate all aspects of CCS technology. This could supersede the interim regulation as soon as CCS is available for full-scale deployment.

For the comprehensive regulatory framework, the TAB project has worked out a detailed proposal for the first time, comprising inter alia:

- Establishing that long-term, safe storage of CO_2 is in the public interest.
- Identifying the sequestration processes that are regarded as suitable in principle and the appropriate regions for this and, possibly, specific sites under a nationwide plan for CO_2 storage (»CCS plan«).

- Creating an integrated licensing process (ILP) with public involvement for concrete CCS projects.
- Defining the fundamental requirements to be met by capture, transport and storage to take precautions against risks to health and the environment, incl suitable monitoring procedures.
- Regulating liability for third-party personal injury and physical damage and for environmental damage not related to climate protection.

Irrespective of whether the proposal, in an overall political assessment, is shared in all details – e.g. the creation of a separate CCS law with ILP – it is a useful starting point for legislative thinking, in the TAB's view.

Also to be considered are the incentives that can be created to ensure that CCS plants are in fact translated into practice. For this, we have several points of attack:

- counting CCS toward the EU Emissions-Trading Scheme, which is closely interlocked with the international climate-protection regime under the Kyoto Protocol;
- specific, political instruments with which CCS can be promoted above all in the demonstration and early market-penetration phases;
- the options for enforcing CCS by taking the regulatory-law route for new and, possibly, existing plants as well;
- other potential tools designed to create incentives for the development of the safest possible storage sites.

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ANNEX

LIST OF TABLES 1.

LIST OF FIGURES 2.

LIST OF ABBREVIATIONS 3.

AAU	Assigned Amount Unit
BBergG	Federal Mining Act
BBodSchG	Act on Protection against Harmful Changes to Soil and on Rehabilitation of Contaminated Sites (Federal Soil-Protection Act)
BGB	Germany's Civil Code
BGBl.	Federal Gazette
BGR	Federal Institute for Geosciences and Natural Resources
BImSchG	Federal Pollution-Control Act
BImSchV	Ordinance on the Implementation of the Federal Pollution-Control Act
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
CCGT	Combined-cycle gas turbine plant; gas and steam power plant
CCS	CO2 capture and storage
CDM	Clean-Development Mechanism
CH4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
ECBM	Enhanced Coal Bed Methane Recovery
EEG	Germany's Renewable Energy Sources
EGR	Enhanced Gas Recovery
EIA	Environmental-impact assessments (UVP)
EOR	Enhanced Oil Recovery

EPPSA	European Power Plant Suppliers Association
EU	European Union
EUA	EU allowance
GGV	Sea Regulation Concerning the Carriage of Dangerous Goods by Marine Vessels
GHGs	Greenhouse gases
GrWV	Groundwater Ordinance
G8	Group of Eight (Italy, Canada, Japan, Germany, US, Russia, UK, France)
HELCOM	Helsinki Convention (Convention on the Protection of the Marine Environment of the Baltic Sea Area)
H_2	Hydrogen
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
KrW-/AbfG	Act on Promoting Closed-Substance Cycle Waste Management and Ensuring Environmentally Compatible Waste Disposal
KWKG	Combined Heat- and Power-Generation Act
LPG	Liquefied petroleum gas
MEA	Monoethanolamine
MeO	Metal oxide
NBBW	The state government Council on Sustainable Development in Baden-Württemberg
NGO	Non-governmental organization
OSPAR	Oslo/Paris Convention (Convention for the Protection of the Marine Environment of the North-East Atlantic)
R&D	Research and development
RohrFLtgV	Ordinance Regulating Pipeline Installations
SO_x	Sulphur oxides
TAB	Office of Technology Assessment at the German Parliament
UBA	Federal Environment Agency
UGB	Environmental Code
UmweltHG	Environmental-Liability Act
USchadG	Environmental-Damage Act
UVP	Environmental-impact assessment
UVPG	Environmental-Impact Assessments Act
UVP-V	Ordinance on Environmental-Impact Assessments
WBGU	German Advisory Council on Climate Change
WHG	Water-Resources Act
ZECA	Zero Emission Coal Alliance

GLOSSARY 4.

Aquifer – Also groundwater reservoir: water-bearing rock body with hollows that is suitable to conduct liquids.

Base period – Comparative period for measuring changes.

Biomass – Organic material in the biosphere.

CDM – Clean-Development Mechanism – One of the flexible mechanisms under the Kyoto Protocol. A country listed in Annex 1 to the Kyoto Protocol can buy »carbon credits« (CERs) from a country not listed there.

CO_2-equivalent – Ratio for the greenhouse-gas potential of substances in the earth's atmosphere. The greenhouse effect of carbon dioxide serves as reference value.

COORETEC – CO_2-reduction technologies in fossil-fired power plants. Research and development initiative of the Federal Ministry of Economics and Technology.

Deep saline aquifer – A very low-lying rock body containing brackish water or brine with high permeability.

Demonstration phase – A technology that is in the demonstration phase and already used in pilot projects or on a small scale, though cannot be fully implemented yet in an economically meaningful way.

Emission factor – The mass of a released (emitted) substance relative to the input mass of a source material. The emission factor is material- and process-specific.

Emissions trade – Trading system in which a fixed amount of emission permits can be bought and sold.

Fugitive emissions – Any release of gases or vapours, e.g. in the processing and transportation of gas or petrol.

Greenhouse gases – Carbon dioxide (CO_2), methane (CH4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorcarbon (PFC), sulphur hexafluoride (SF6).

Greenhouse-gas inventory – Comprehensive emission statistic pursuant to the stipulations of the Framework Convention on Climate Change.

IGCC – Integrated Gasification Combined Cycle – Process for energy generation in which hydrocarbon or coal is converted into gas, which can be used as fuel in gas or steam turbines.

Injection – Pressing liquids into the interstices of rocks under pressure.

Joint Implementation – One of the flexible mechanisms under the Kyoto Protocol for the reduction of emissions. If a state is listed in Annex I to the Kyoto Protocol, it can buy additional emission permits from another state listed there by taking emission-reducing measures.

Kyoto Protocol – The Kyoto Protocol is an additional protocol adopted in 1997 to give a final shape to United Nations Framework Convention on Climate Change with the aim of climate protection.

Leakage – In projects for lowering greenhouse gases, the escape of GHGs going beyond the amount estimated for the project is called leakage. In CO_2 storage, leakage refers to the escape of CO_2 from its storage facility into water and/or the atmosphere.

London Convention – Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter which was passed on 29 December 1972.

Mineralization – A process in which CO_2 which was injected into a rock body reacts with silicate minerals and forms stable carbon compounds.

Monitoring – A process in which the amount of stored CO_2 is measured and its position and behaviour underground observed.

Storage facility/reservoir – Subterranean rock body of sufficient permeability to store and conduct liquids.

BÜRO FÜR TECHNIKFOLGEN-ABSCHÄTZUNG
BEIM DEUTSCHEN BUNDESTAG

KARLSRUHER INSTITUT FÜR TECHNOLOGIE (KIT)

Neue Schönhauser Str. 10

10178 Berlin

Fon +49 30 28 491-0
Fax +49 30 28 491-119

buero@tab.fzk.de
www.tab.fzk.de