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Ecological, Economic and Structural Comparison of Renewable Energy Technologies (RE) with Carbon Capture and Storage (CCS) — An Integrated Approach

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Status Quo and the Aims of the Study

Long-term scenarios on the development of energy systems show that the transition to a climate-friendly energy supply will in some way rule out coal. However, coal is the fossil fuel with the largest global reserves – distributed over many regions of the world – and is subject to fewer geopolitical risks than oil and gas.

This raises the question of how the use of coal could be made more climate-friendly. Alongside improvements in the efficiency of the various ways coal is used (primarily by increasing the conversion efficiency of power stations and expanding the use of combined heat and power) the technology option of carbon capture and storage (CCS) could also make a contribution. Its introduction could make it possible to produce 'low-CO_2' energy based on coal. The important fields in this context are electricity generation, and even more so the production of hydrogen as a universal storable fuel. The same also applies in principle to natural gas and oil, although from the climate perspective natural gas is a less critical issue owing to its lower carbon intensity.

There are still many unanswered questions today concerning the possibilities of capturing CO_2 and especially storing it safely for a very long time. These questions include not only how much safe, long-term storage capacity there actually is for CO_2 (and its regional distribution), but also what costs and ecological risks are involved. If CCS can be successfully introduced as a new technology option at reasonable cost and with acceptable ecological impacts, it could make a major contribution to providing a more secure and climate-friendly supply of energy.

Previous studies in this field have tended to concentrate on the general technical feasibility of the concept. There has not yet been a detailed examination of the ecological, economic and social impacts along the whole process chain (e.g. energy balance, cumulative energy demand, environmental impact, use of resources, risks, costs) of the kind that is a matter of course today for other new technologies, especially renewables. Only after such scrutiny will it be possible to decide how environmentally beneficial this technology option really is, what advantages and disadvantages it has compared with renewables and what contribution it can make to a sustainable economic structure. That is the focus of the present study.

This project is particularly relevant in view of recent political initiatives on international level for using the so-called 'clean coal' option, extensive research activities globally and the publication of the German Environment Agency's assessment of CCS from the sustainability perspective in mid-2006.

More and more scientists, politicians, and NGOs are calling for investigation and consideration of 'clean coal' technology. The energy sector itself is planning to open various small CCS demonstration plant in 2008 and the following years mainly in Europe and USA.

The findings so far show that introducing carbon capture and storage only makes sense if done on a large scale. Given the great volume of investment required and the implications for other options for reducing greenhouse gases, the decision about whether CCS should be made a central pillar of energy policy will have to be thoroughly considered on a solid scientific basis. It is already recognised today that new technologies will have to satisfy numerous technological, structural, economic, ecological and social criteria before they can be regarded as viable options for a sustainable future energy supply. So they will be subjected to a rigorous selection process before their suitability as future key technologies is accepted. As well as detailed investigation of the potential, the achievable future costs, the implications for industrial policy and social impact of a technology, differentiated life cycle assessments (LCAs) of the whole system represent a suitable instrument for assessing the practicability of new technologies against various sustainability criteria. Very detailed LCAs are already available for the various technologies based on renewables, which represent one of the main other options for avoiding greenhouse gases. Suitable data for making a solid assessment of capability and environmental and system impact are also already available for numerous technologies in the field of efficiency (e.g. modern combined heat and power).

The goal of this project is consequently to weigh up the range of technologies for carbon capture and storage currently under discussion in terms of their fundamental suitability for a future energy supply. We outline several reference systems and realistic system configurations for supplying electricity and hydrogen together with all the relevant data required to properly appraise and assess the options in the scope of an overall concept for a future sustainable energy supply. These make it possible to identify the fundamental potential of the proposed technologies, the technological advancements still required and the environmental impact. A systematic comparison with other options for a climate-friendly energy supply – especially the use of renewables – concludes the study. This is the context in which the discussion about the possible role of the CCS option in longer-term energy supply scenarios must be conducted, in which the timeframe of future development steps (establishing an infrastructure) must be considered and in which fundamental energy policy decisions must be addressed. This investigation supplies a sophisticated set of data for placing the carbon capture and storage option in the energy and especially the climate policy context. As such it can make an important contribution to energy policy decisions currently on the agenda.

The principle research questions can be summarised as follows:

- What are the conceivable routes for CCS (technologies, infrastructures, development timetables)?
- What does the overall life cycle assessment of these processes look like, and how does low-CO_2 fossil-based electricity compare with CO_2-free options, especially renewables (comparison on an equal footing)?
- What role can CCS play for climate protection in comparison with other relevant options, and when (systematic comparison on the basis of significant criteria such as cost, timeframe, ecological restrictions, etc.)?
- What role can CCS play as a possible bridge to a renewable energy system?

The report has **five parts**:

Part one (introduction and background) examines the driving forces behind CCS and the attitudes of relevant actors.

Part two takes a closer look at technological developments in the field of CO_2 capture (in electricity generation and hydrogen production) and at the individual steps involved in CO_2 capture, transport and storage.

The **third part** presents a comparative assessment of CCS and other relevant climate protection technologies on the basis of a comprehensive set of criteria. The life cycle assessment method (LCA) is used to conduct a thorough comparison of the ecological performance of CCS in comparison with continued expansion of renewables. The economic parameters are also examined in greater depth. Additional criteria are used to differentiate and expand the comparison with renewables.

Part four examines the significance of CCS for national energy sectors, including thorough system and scenario analyses. The significance of CCS and renewables for energy and climate policy are compared. The Germany energy system was chosen as an example.

Finally, **part five** turns to a more global perspective on CCS, showing the requirements and preconditions that have to be met for international implementation of this technology option.

Summary of Theses

Driving Forces and the Attitude of Relevant Groups Towards CO_2 Capture and Storage

- Climate protection is the most important reason for developing CO_2 capture and storage. In particular sectors of the economy other economic incentives to capture CO_2 already exist today (e.g. enhanced oil recovery).

- Attitudes towards the technology are not uniform in different groups of society. CCS is often described as a possible bridge to the era of renewable energy.

- Environmental organisations prioritise the further expansion of renewables and the full exploitation of energy-saving potentials. All environmental organisations reject the idea of storing CO_2 in the oceans. Adequate proof of long-term stability is demanded for all storage options.

CO_2 Capture Methods

- Today there are three technology options for CO_2 capture in the short to medium term. Capturing CO_2 from the flue gases of conventional power stations (*post-combustion* capture) leads to a significant increase in electricity generating costs, causes a considerable increase in fuel consumption and substantially reduces power station efficiency. In principle the technology is already available today, although it has yet to be demonstrated at the scale of commercial power plant.

- Capturing CO_2 *before* combustion (*pre-combustion* capture) in coal- or gas-fired power stations with integrated gasification (IGCC and natural gas combined cycle) is from today's perspective a more advantageous process than capturing CO_2 from flue gas. Implementing this CO_2 capture method would require considerable improvement and development, especially with regard to scaling it up to conventional power plant dimensions.

- The *oxyfuel* process involves burning fuel in pure oxygen and currently offers the best prospects for CO_2 capture in terms of the achievable overall efficiency of the process and possibly also the resulting costs, because the components involved are largely based on conventional power station technology. A precise evaluation is not yet possible, because the process is only at the beginning of the demonstration phase.

- Considerable additional costs must be factored in for capture at the power station, according to current estimates between €35/t and €50/t CO_2. Through research and demonstration projects and other technological improvements it is aimed to reduce the costs to less than €20/t CO_2.

- As well as planning new builds with integrated CO_2 capture it is in principle also possible to retrofit. Because of the strong increase in energy consumed internally, this only makes sense in power stations which start off with a sufficiently high level of efficiency. In terms of technology, flue gas scrubbing is the primary option for retrofitting from today's perspective. When power stations are planned today, the option of designing them to be 'capture ready' (prepared for retrofitting CO_2 capture) should be considered.

Methods for CO_2 Transport

- Energy efficiency, economic and ecological considerations mean that pipelines (onshore, possibly offshore too) and large tanker ships are the only relevant transport options for large-scale implementation of CCS.

- The decisive parameters for the source/sink relationship are in particular transport distance and capacity, but coordinating the timing of planning, approval and construction of power stations, pipelines and CO_2 sinks is also relevant. The high investment costs involved in establishing a CO_2 infrastructure necessitate forward-looking planning and coordination between the different parties involved.

- Both gas conditioning (liquefying CO_2 by compression, which reduces power station efficiency by up to 3.5 percentage points) and subsequent CO_2 transport themselves require a more than negligible additional amount of energy, which in turn causes additional CO_2 emissions (and other greenhouse gases and pollution).

- The range of cost estimates for CO_2 is – depending on transport distance and capacity – approx. €1/t to €10/t (for pipeline or ship transport) and represents about 10 % of the total costs of the CCS process (capture, compression, transport, storage).

- In relation to the other infrastructure costs (electricity transmission, fuel logistics) the cost of CO_2 transport is likely to be a secondary factor when selecting power station sites. Also, existing power station sites are often likely to be retained for reasons of public acceptance.

- Transport of fuel (oil, oil products, coal) already represents a large proportion of total freight transport in industrialised countries. Introducing CCS on a large scale would considerably increase transport volumes – to supply additional coal and remove CO_2. There would also be a risk of pipeline or shipping accidents, although the risk per ship or kilometre of pipeline is relatively small.

CO_2 Storage: Methods and Capacity

- For various reasons the storage possibilities for CO_2 are limited, both globally and nationally. Owing to the many uncertainties involved, current estimates of actual storage potential vary enormously. Global estimates show that although the potential is certainly considerable, in the long term it will certainly not be possible to solve the climate problem through CO_2 storage alone.

- Ecological, economic and capacity considerations mean that the only option e. g. for Germany is geological storage in empty gas fields and deep aquifers. Taking into consideration only the country's major point sources and factoring in an average increase in energy use for CCS of 30 %, the static range in Germany is between thirty and sixty years.

- Guaranteeing very low leakage rates is essential for the acceptance of underground storage. Corresponding evidence will have to be provided in a comprehensible form.

- Little is yet known about the behaviour of CO_2 in underground reservoirs. Research projects already under way should greatly improve knowledge of drilling and injection methods, distribution of gases in reservoirs and monitoring methods.

Comparative Life Cycle Assessments

- From a holistic perspective the terms *zero-carbon*, *zero-emissions* and *CO_2-free* are misleading regarding fossil fuelled electricity generation and hydrogen production. When the supply chain is taken into consideration and the usual assumptions are made about CO_2 capture rates at the power station (88 % for post-combustion and pre-combustion) the potential for net CO_2 reduction is found to be between 72 % and 78 %. If the full range of greenhouse gases is included, the reduction compared with a power station without CCS falls to a range of 67 % to 78 %. Higher CO_2 capture rates of up to 99.5 % (achievable with the oxyfuel process) allow in a coal-fired power station a net CO_2 reduction of 90 % and a net greenhouse gas reduction of 78 %.

- In this context it is more correct to speak of *low-CO_2* or *low-carbon* electricity generation. The CO_2 emissions from the 'best' fossil-fuelled power station from the climate protection perspective (natural gas combined cycle, NGCC) are 'only' 50 % higher than those from the 'worst' CCS power station (coal-fired thermal power station with post-combustion capture).

- The increased fuel consumption involved in CO_2 capture and storage always leads to a proportional worsening of the outcome in the other impact categories. There are, however, exceptions: with *post-combustion* capture other emissions are reduced through reaction with the solvent – acidification falls by 10 % and PM10 equivalents (particulate matter) increase by only about 2 %. On the other hand, eutrophication increases by 36 % and summer smog by 94 %, and demand for cooling water increases by up to 50 % (post-combustion).

- In comparison with CCS power stations, comparable large-scale renewable energy systems (e.g. solar thermal power stations, offshore wind farms) fare considerably better in all impact categories across all stages of the process. Innovative fossil-fuelled power station solutions like natural gas combined cycle (NGCC) including heat extraction and combined heat and power plant units (CHP) available today are comparably environmentally friendly as CCS plant are expected to be in 2020.

Other Ecological Assessment Factors for CCS

- As well as direct and indirect effects on the appearance of the landscape (e.g. caused by increased fuel consumption) and the negative consequences of increased transport volumes (of CO_2 and additional fuel), the greatest other ecological impact would be the potential unplanned release of stored CO_2 and the direct influence of the stored CO_2 on the immediate vicinity of the sink over the course of time.

- The different CO_2 storage options differ from one another – sometimes considerably – in terms of ecological and safety considerations. Geological sinks (e.g. saline aquifers) are considered to have comparatively high long-term stability, but there is still great uncertainty concerning the underground movement of CO_2 and the resulting consequences.

- Regarding CO_2 storage in oceans its impact on marine ecosystems is still largely unresearched, but the expectable risks are so great that most countries rule out even conducting further research into this storage option.

Economic Comparison of CCS and Renewable Energy Technologies

- In terms of electricity generation costs, a general structural difference must be noted when comparing CCS and renewables. Large or very large cost degression and learning effects are still to be expected in both fields, but in the case of CCS these will be counteracted by further rises in fuel prices. This effect is particularly strong in the case of gas-fired CCS power stations.

- It can be assumed that electricity from renewable energies will become economically competitive to fossil-fuel based electricity earlier with the introduction of CCS. By 2020 – the earliest point at which CCS technologies are likely to be commercially viable – a whole range of renewable energy technologies is likely to be able to supply electricity at cost conditions comparable to or better than fossil-fuelled power stations. In the longer term, renewables can be expected to have considerable cost advantages due to their independence from fuel price fluctuations.

- The relative profitability of CCS and renewables is currently still subject to many uncertainty factors. The aforementioned predictions for renewables are based on assumptions of dynamic market development on a global scale, allowing very substantial cost degression effects to be exploited through mass production and learning curve effects.

- When it comes to hydrogen, production using renewables cannot be expected to become competitive with production using fossil fuels (including CCS) in the foreseeable future. Whether or not this is the case, hydrogen is unlikely to become an important factor in the energy economy for several decades due to its generally high costs and the considerable infrastructure challenges associated with its introduction. But in principle this option represents an interesting strategic element for the transport sector – today still largely dependent on oil – and could potentially supplement biofuels as a diversifying element.

The Role of CCS in Industrialised Countries: the Example of the German Energy Supply System

- The energy systems of industrialised countries are characterised by a number of shared features. Firstly, there is great potential for energy efficiency measures, on both the supply and demand sides. Secondly, the growth in energy consumption, and consequently in energy-related greenhouse gas emissions, is in general much slower than in developing countries. The special case for Germany is that it faces the complex challenge of having to replace a large proportion of its power station capacity within the coming fifteen years. The following theses are formulated for Germany, but are also applicable to other industrialised countries:

- As the main element of a climate protection strategy (the CCSMAX scenario) CCS runs into structural and capacity limits. The earliest date when CCS technologies are expected to be ready for implementation is 2020, which is too late for the first wave of the necessary power station replacements, which has just begun. It would necessitate extremely rapid growth rates for CCS plant between 2020 and 2050 and speedy establishment of a hydrogen infrastructure.

- If a vigorous political course of promoting renewables and efficiency improvements is pursued over the next ten to fifteen years, the realisation of energy-saving potential and the successive expansion of renewables would be able to make a more rapid contribution to climate protection than CCS. Increasing energy productivity makes sense in purely economic terms, too. Both strategy elements are also associated with strong innovative stimuli for taking a share of growing global markets. Considerable increases in efficiency and the further expansion of renewables are absolute preconditions for effective climate protection. If a sustained high rate of implementation is maintained, as described in the NaturschutzPlus (NATP) scenario, the use of CCS technologies is not absolutely necessary for meeting even ambitious climate protection targets. The strategy outlined in NATP is the best for the economy as a whole in the medium to long term, and should therefore be an aim of energy policy.

- The period until 2020 should be used to thoroughly explore the development and cost-cutting potentials of CCS technologies and to demonstrate the technological feasibility. If that process proves successful, CCS would offer the possibility, as described in the BRIDGE scenario, of switching to a climate-friendly path even if it has not proved possible to sustain the ambitious pace of implementation of efficiency potentials and renewables over time. In view of the real interests involved in the field of energy, especially in the global context (where energy saving efforts are counteracted by substantial growth trends), this constellation may well become reality.

- The successive introduction of CCS after 2020 (presuming the availability of suitable sinks with long-term stability) can act as an ancillary element helping to make it easier to maintain the sustained efforts that will be required to further improve efficiency and expand renewables. In this situation CCS can attain significant importance in fulfilling a bridging function to the establishment of a renewable energy economy. Consequently, it would appear that further development efforts for CCS are necessary and in the international context of climate protection indeed unavoidable. But this must not occur at the expense of R&D efforts in the field of efficiency and renewables.

- Overall it must be ensured that measures for establishing a CCS infrastructure are compatible with the further expansion of renewables and that permanent structural commitments and use conflicts (for example with geothermal energy or decentralised CHP) are avoided.

- If CCS is included as a climate protection element, upcoming power station planning processes must already begin considering the possibility of future implementation of CCS. The idea of designing new builds ‘capture ready’ is central here, and is reinforced by discussions at the EU level about possibly making ‘capture ready’ status obligatory for all new power stations in the medium term.

CCS in the International Context

- Above all at the global level CCS could, from today’s perspective, make a noticeable contribution to meeting ambitious climate protection goals alongside renewables and energy efficiency. Under plausible assumptions CCS could also help to reduce the economic costs of climate protection if today’s expectations about its technological development (especially the cost-cutting possibilities) prove to be realistic. Including CCS in an integrated overall concept seems to be one option to stabilise the CO_2 concentration in the atmosphere at 450 ppm with an acceptable level of loss of economic growth. This applies in particular if the alternative investment required in measures to adapt to the looming climate change is taken into account.

- Internationally too, CCS can fulfil a ‘bridging function’ to an emission-free energy system, but only if the technologies are available in time for large-scale implementation and the costs of fossil fuels do not rise too steeply.

- The large-scale introduction of CCS presupposes that an institutional framework will be established (preferably at the international level) to sensibly regulate responsibility for the risks stemming from CCS (giving consideration to the precautionary and polluter pays principles) and offer involved parties an incentive to guarantee the safety of storage.

- Plausible proposals already exist for the shape of such an institutional framework (e.g. carbon sequestration bonds), that could be integrated in the existing climate protection regime and via market mechanisms involve the public in decisions about the use of CCS.

- Further research – and also political decisions – are required concerning the development and discussion of the institutional framework, especially integration in the mechanisms of the UN Framework Convention on Climate Change, the development of liability mechanisms and the implementation of legal provisions to restrict local risks associated with CCS.

- In upcoming climate protection negotiations CCS could improve the chances of persuading more states (e.g. United States, China) to undertake firm obligations on emissions, because it would allow them to retain their familiar structures and their domestic primary energy base.

- Ultimately, for reasons of capacity (limited storage potential and finite fossil energy resources), CCS cannot obviate the global need for further expansion of renewables and a considerable increase in energy efficiency. But under particular conditions CCS can help in meeting ambitious climate protection targets while at the same time extending the time available for the necessary restructuring of the energy system.

Summary

Background and Introduction

In recent years the discussion about carbon capture and storage (CCS) has moved steadily up the agenda in many countries as well as globally in the context of meeting climate protection targets – even more so as oil and gas prices have risen sharply and the increasingly urgent debate over security of energy supplies has swung towards greater use of coal.

Carbon capture and storage technologies are not fundamentally new. Some of them are already used on an industrial scale and finds commercial application in oil extraction (enhanced oil recovery to increase the extraction rate of oil fields) or for conditioning natural gas (separating off the accompanying CO_2). However, for the much larger volumes that would generally be involved in application in power stations or for centralised hydrogen production numerous questions still remain unanswered. That also applies to the field of transport, to the possible configurations of a CO_2 infrastructure and to storage. Demonstration projects (e.g. in Germany: 30 MW_{th} pilot plant using the oxyfuel process, planned start of operation 2008) and the first semi-commercial test facilities (the German company RWE Power AG plans to construct a coal-fired power station with integrated gasification, CO_2 capture and storage with a net output of 360 MW_{el} by 2014) aim to achieve significant progress in developing the technologies at the scale required for power stations.

Studies so far conducted in this field have concentrated largely on the technical feasibility of carbon capture and storage. There has not yet been a detailed investigation of the ecological, economic and social impact across all stages of the process (e.g. energy balance, cumulative energy demand, environmental impact, resource consumption, risks and costs) of the kind that is today a matter of course for other new energy technologies, in particular renewable enery technologies. Only after such a study has been completed will it be possible to decide how environmentally beneficial the CCS option really is, what its benefits and drawbacks are compared to renewables and what contribution it can make to a sustainable economic structure. Including carbon capture and storage in the fossil fuel cycle makes it possible for the first time to conduct a comparison with renewables on equal terms (with respect to climate policy). Such a comparison, made on the basis of a comprehensive set of criteria, is the main object of the present study, answering the following questions:

- What are the conceivable paths for carbon capture and storage (technologies, infrastructures) and how do they fit on the time axis (development periods)?
- How do the LCAs of these processes look, and how does low-CO_2 fossil electricity generation compare with CO_2-free options (especially renewables) in this respect?
- What role can carbon capture and storage play for climate protection in comparison with other relevant options, and when (systematic comparison on the basis of significant criteria such as cost, window of opportunity, ecological restrictions, etc.)?
- What role can carbon capture and storage play at the national and international levels as a possible bridge to a renewable energy system?

Driving Forces and the Attitudes of Relevant Groups towards Carbon Capture and Storage

Several different motivations are central to the development of technologies for capturing, transporting and storing CO_2. Alongside climate protection as the overriding motivation, questions of security of supply, technological aspects, and in some cases also very real commercial considerations (e.g. measures in the field of enhanced oil recovery in countries with a CO_2 tax such as Norway) play a decisive role. Technology that can generate progress in international climate protection negotiations is of particular importance. Among the supporters of CCS are – above all – those states that have so far adopted a rejectionist or wait-and-see stance in the international climate protection process, such as the United States. The United States has also made CCS a central priority of the Asian Pacific Partnership (APP), a more technology-oriented climate protection agreement that represents a counterpole to the Kyoto Protocol.

Not least for these reasons, carbon capture and storage has become the subject of a broad range of networks at the international level, such as the Carbon Sequestration Leadership Forum (CSLF), which was initiated by the United States in 2003.

The attitudes of actors in society towards CCS differ rather widely. Across the world environmental and nature conservation **NGOs** (non-governmental organisations) – with very few exceptions – agree on the following points and demands concerning CCS:

- CO_2 must not be stored in ecosystems (namely, oceans),
- Long-term stability of storage systems must be demonstrably proven and guaranteed,
- Development of CCS must not be at the expense of R&D funding for renewables, and
- Renewable energy sources and more rational use of energy are preferable to CO_2 storage, and their implementation should be stepped up.

That is as far as the consensus extends internationally. German NGOs, for example, are generally at the more sceptical end of the international spectrum in their attitudes to CO_2 storage.

Political parties, too, differ in their positions on the technology. In Germany, for example, they range from the expectation that low-CO_2 fossil-fuelled power stations will represent 'an important pillar' of energy policy (the conservative CDU) to the call for a coordinated research campaign (the social democratic SPD) or clear rejection (the left-wing Die Linke).

The positions of the different German **ministries and expert committees** can be summarised as follows: The Federal Ministry of Economics (BMWi) is supporting carbon capture and storage through the COORETEC research programme. This wide-ranging research programme is designed to allow the process of replacing and expanding capacity in the fossil-fuelled power sector that will begin around 2010 to be conducted at a high technological standard. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Environment Agency (UBA) believe that there are still many unanswered questions to be resolved before CCS can be regarded as a safe long-term option that is acceptable in social, ecological and economic terms. In a comprehensive investigation the UBA has examined carbon capture and storage in terms of sustainability criteria, and has come to the conclusion that CCS is a set of non-sustainable technologies that can at best represent a transitional solution.

In its position paper the Council for Sustainable Development calls carbon capture and storage a potentially important bridge 'to the era of renewable energy supplies'. To this end, it believes, CO_2 capture technologies should be integrated in highly efficient power stations, but only from the point of view of economic efficiency. The German government's Advisory Council on Global Change (WBGU) has taken a firm stance in favour of storing carbon dioxide, referring in this connection to an 'end-of-pipe technology' that can make a contribution to climate protection for a limited period of time. It rejects the storage options in ocean waters (ecological reservations and missing long-term effect), biomass (lack of potential for expansion) and saline aquifers (no guarantee of safety and long-term storage). Exhausted oil and gas fields could be used temporarily, but only if a sufficient retention period can be guaranteed. In terms of storage period, the WBGU has called for secure sequestration for at least 10,000 years. The WBGU believes storage under the seabed to be permissible only under certain conditions. The Advisory Council on the Environment (SRU) believes that carbon capture and storage may be too expensive in comparison with other CO_2 avoidance options, and that the technologies may also come too late for the upcoming expansion and replacement of power station capacity.

Industrial Associations are definitely positive about CCS as a long-term option, but often prioritise improving the efficiency of the power station process as a contribution to climate protection. Capture of CO_2, as previously mentioned, already offers opportunities for the oil and gas industry today.

CO_2 Capture Methods

This investigation of carbon capture and storage in the use of fossil fuels has restricted itself to the field of electricity generation in power stations and the potential future production of hydrogen by means of coal gasification – in other words to plants emitting particularly large amounts of CO_2 centrally (point sources). In terms of reducing CO_2 emitted through the use of fossil fuels, efficiency-improving technologies have previously been the main focus of attention. Applying these technologies quickly over the past decades has achieved a continuous increase in power station efficiency (despite stricter environmental regulations that have in some cases led to increased fuel requirement). The efficiency levels achievable today are 43 % for lignite-fired power stations and 46 % for coal-fired power stations, while for gas-fired power stations 58 % efficiency is now possible. For reasons of thermodynamics and materials technology this trend cannot continue forever. So a further significant reduction in CO_2 emissions from fossil electricity generation will require the application of CO_2 capture techniques (which are largely already known today) or a move to innovative new power station technologies that include CO_2 capture (e.g. chemical looping combustion).

CO_2 capture technologies are more likely to become available in the medium term (large-scale application is unlikely to occur before 2020) while the development of new, innovative power station concepts should be regarded more as a long-term option (see Fig. 1). Disadvantageous for CO_2 capture is the high energy requirement for the capture process itself, which leads to significant reductions in efficiency (in some cases 10 percentage points and more) and significantly reduces

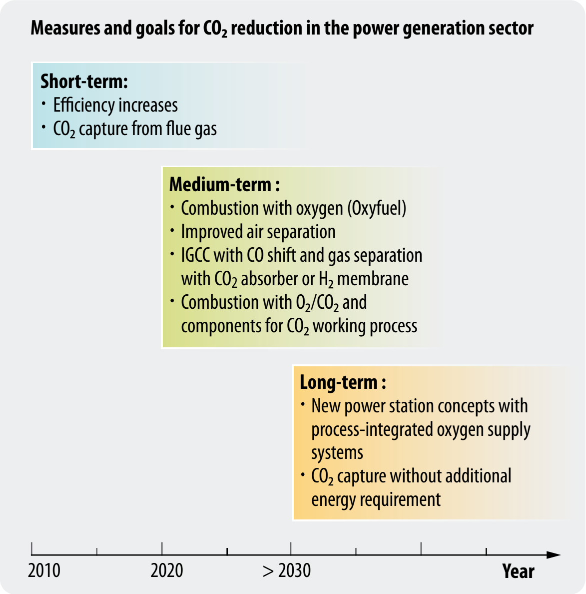

Fig. 1: Measures and goals for CO_2 reduction in the power generation sector

the levels of efficiency achieved today (roughly to the level of twenty or thirty years ago). This means that CO_2 capture would lead to a significant increase in electricity generating costs and cause a considerable increase in fuel consumption, the logistics of which must also be taken into account. For power stations constructed around 2020, estimates of the cost of CO_2 capture at the power station (which dominates the additional costs of carbon capture and storage) currently vary between €30 and €60/t CO_2. Various research, demonstration and pilot projects aim to significantly reduce these costs, with the goal of bringing the overall cost of the whole CCS process (including transport and storage) down below €20/t CO_2.

From today's (technology) perspective there are three relevant options for CO_2 capture in the short to medium term (see Fig. 2). **Flue gas scrubbing** will probably be an adequate option for retrofitting, especially if it turns out to be possible to reduce the energy required still further through new scrubbing agents. Implementing **integrated coal gasification** (IGCC) would require much greater availability, which is not yet adequate for the power station scale. The crucial point for the **oxyfuel** process will be to collect experience and successfully put the lessons learned into practice (e.g. through the demonstration project at Schwarze Pumpe in Germany, launched in 2006 by Vattenfall).

The method of **capturing CO_2 from flue gases** in conventional power stations (**post-combustion capture**) is basically available today, but has not yet been demonstrated on a commercial power station scale. In the longer term this technology is unlikely to become widely established unless its energy consumption can be reduced significantly.

Pre-combustion capture of CO_2 in coal- or gas-fired power stations with integrated gasification combined cycle (IGCC and natural gas combined cycle, NGCC) is from today's perspective a better method than flue gas capture of CO_2. Apart from its higher efficiency levels, the prime advantage of this technology lies in its flexibility both in terms of fuel (coal, biomass, substitute fuels) and in terms of product (electricity, hydrogen, synthetic gas and liquid fuel). The next step here is large-scale technical demonstration. The IGCC technology itself – without CO_2 capture – has already been tested in several plants (e.g. Buggenum in the Netherlands and Puertollano in Spain). Before CO_2 capture is implemented there will be a need for improvement and development of individual components (e.g. hydrogen turbines). In Germany RWE Power intends to take the first step towards implementing this technology by building a full-scale IGCC power station with CO_2 capture (output (450 MW_{gross} / 360 MW_{net}) by 2014.

The **oxyfuel process** (combustion in pure oxygen) currently offers the best prospects for CO_2 capture in terms of achievable overall efficiency of the process (and also the resulting costs), because it is largely based on conventional power station components and technology. It is not yet possible to provide a precise assessment because the process is still at the beginning of the demonstration phase. At Schwarze Pumpe in eastern Germany Vattenfall Europe is building the world's first pilot plant for lignite combustion using the oxyfuel process. The Vattenfall pilot plant, which has an output of 30 MW (thermal), will be used for research and development purposes with the aim of developing the new technology to the point where it is commercially viable. It is scheduled to begin operation in 2008 after a construction phase lasting about three years. Initially the CO_2 will not be stored, but corresponding concepts (e.g. transport options) are being investigated.

Whether CO_2 capture technologies become relevant for power station replacement will depend on political and economic circumstances. The lack of incentives for retrofitting existing power stations with CO_2 capture has meant that this option has not been relevant to date. In order to be prepared for future developments it might make sense to build new power stations 'capture ready' (prepared for retrofitting with CO_2 capture). That discussion is already under way.

The space required for the additional components can place restrictions on the implementation of CO_2 capture and storage. Connection to suitable storage and transport infrastructures is also a significant location factor.

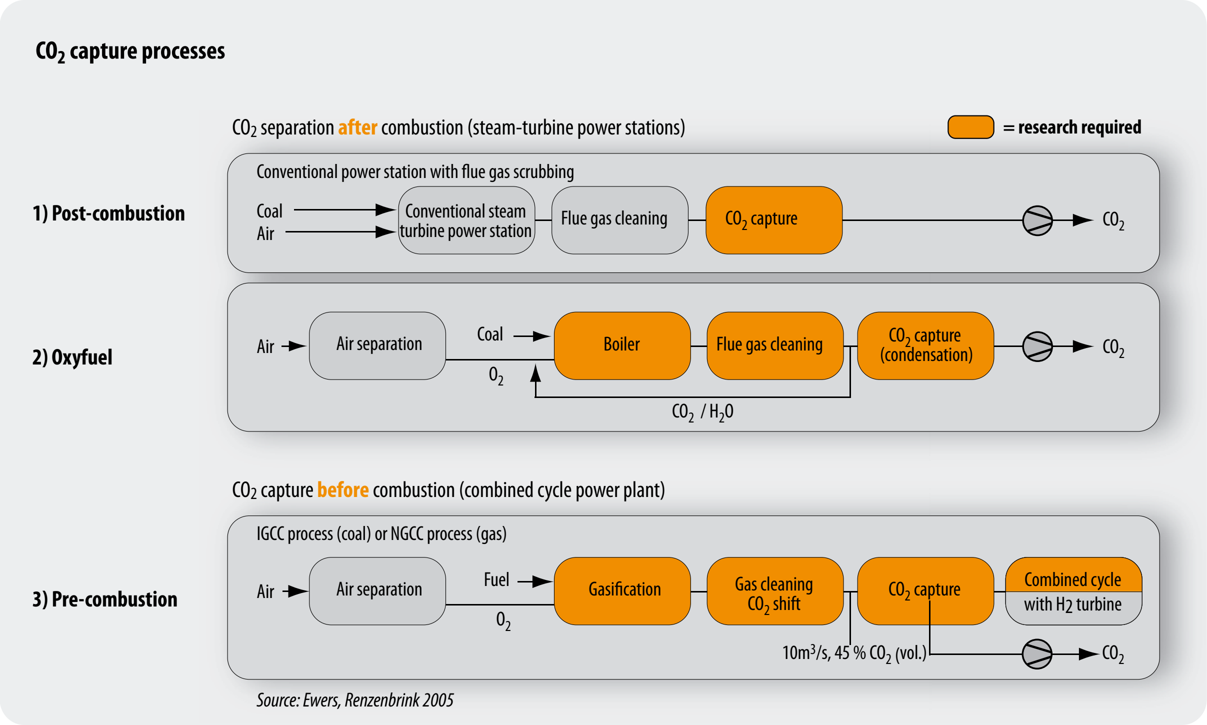

Fig. 2: Methods of CO$_2$ capture at the power station

CO$_2$ Transport Methods

Because of the considerable transport volumes that occur with CCS, the main issue when analysing locations for sources and sinks is to reduce transport distances and costs to a minimum. Case studies show that the specific transport costs can vary very considerably from case to case. Even if the cost of transport appears small in comparison with the cost of CO$_2$ capture at the power station, the aspect of cost efficiency of CCS-related transport will have to be included when selecting locations for new sources.

Alongside transport distance, the question of the general accessibility of the various transport infrastructures that are suitable for CCS is an initial parameter for location analysis. Wherever it is possible to use existing bulk-capable means of transport and transshipment facilities there will be potential for reducing transport costs.

From the energy efficiency, economic and ecological perspectives the only relevant options for large-scale CO$_2$ transport are pipelines (onshore and possibly offshore) and large tanker ships (depending on the location conditions barges or seagoing vessels for offshore storage). The advantage of the pipeline is that it can transport very large quantities of CO$_2$ without interruption at relatively acceptable environmental and financial cost. But constructing a CO$_2$ pipeline infrastructure would be a time-consuming process and would tie up considerable capital; this would only appear reasonable for long-term usage (> 20 to 30 years). Ships, on the other hand, are more flexible and more quickly available, but require intermediate storage facilities and loading/unloading infrastructure. With inland waterways the restrictions on availability during periods of low water levels must be taken into consideration. Transporting CO$_2$ by road and rail tanker is an option only for small quantities and will therefore probably only be relevant for the demonstration and launch phase (see Table 1).

The high investment costs involved make it especially important to coordinate the timing of planning, approval and construction of power stations, pipelines and CO$_2$ sinks. So establishing a CO$_2$ infrastructure necessitates forward-looking planning and coordination between the different parties involved.

Unlike the case of pipeline transport, there has so far been practically no experience in transporting CO$_2$ by ship. However, because CO$_2$ has similar physical properties to LPG (liquefied petroleum gas), experience with LPG transport is partially applicable to CO$_2$ transport.

Both the aforementioned transport options require gas conditioning in order to transport the CO$_2$ in the densest possible form (liquid or supercritical). Pipelines require conditioning to high pressure (approx. 80 to 120 bar), while tankers require very low temperatures at ambient pressure (low-temperature tankers) or temperatures below normal combined with pressure above normal (hybrid tankers).

Mode of transport	Capacity in Mt/a	Availability	Cost in €/t (250 km)	Infrastructure already exists at source/sink?	Comments
Seagoing tanker	< 50	Always	< 1	Almost never	Generally requires multi-mode transport
Inland waterways	< 10	Seasonally restricted (water levels)	approx. 1	Sometimes	Barges not seagoing, time restrictions
Pipeline	< 100	Always	approx. 1.5 (function of diameter)	Will almost always have to be constructed from scratch (largely investment)	25 year operating period, higher costs in built-up areas
Rail	< 1.2	Always	approx. 5	Generally	Noise
Road	< 0.5 Mt/a	Restricted in winter, congestion	approx. 25	Always	Cost, noise and emissions, acceptance, time restrictions

Table 1: Characteristics and suitability of different modes of transport for CO_2 transport

Both gas conditioning and CO_2 transport require quite a lot of energy, normally electricity for compression and/or cooling. According to current knowledge the energy required for CO_2 compression is equivalent to an efficiency loss at the power station of about 2 percentage points (for gas-fired power stations) to 3.5 percentage points (for coal-fired power stations). This additional energy requirement causes additional CO_2 emissions. Estimates of additional (energy-related) CO_2 emissions associated with CO_2 transport vary greatly, especially in relation to transport distance and capacity. Here additional (energy-related) emissions of 1 % to 4 % per 1,000 km are expected for ship transport and 1 % to 2 % per 1,000 km for pipeline transport.

The range of average cost estimates for CO_2 transport by pipeline or ship is between about €1 and €10/t (depending on mode of transport, distance and capacity) and represents about a 10 % share of the overall costs of the CCS process (comprising capture, compression, transport and storage). In relation to the other infrastructure costs (electricity transmission, fuel logistics) the cost of CO_2 transport is likely to be a secondary factor when selecting power station sites. Also, existing power station sites are often likely to be retained for reasons of public acceptance.

Already today, fuel (oil, oil products, coal) represents a large share of goods transport. Introducing CCS on a large scale would increase freight volumes considerably, through the supply of additional coal to power stations and the removal of CO_2.

Safety statistics for existing CO_2 pipelines (in particular in the United States) show a smaller leakage risk than for pipelines carrying natural gas or hazardous substances; nonetheless, routes should avoid densely populated areas where possible for reasons of safety. In populated areas safety measures against leakage and overpressure are required. Although the relative risk associated with ship transport is also predictable, large-scale introduction of CO_2 tankers for CCS would increase the absolute risk of shipping collisions and tanker accidents.

CO_2 Storage Methods and Capacity

There are various different ways to withdraw CO_2 from the atmosphere. A distinction must be made between utilisation for technical and chemical purposes (e.g. producing carbonic acid, dry ice and feedstock for polymer chemistry), storage in geological formations (e.g. saline aquifers), sequestering CO_2 in the marine environment either directly (e.g. depositing it in the ocean depths) or indirectly (e.g. algae formation) and withdrawing CO_2 from the atmosphere by intentionally growing biomass (e.g. forestation). A mineralisation process for binding CO_2 to silicates is also under discussion (especially in the United States) but it is still in the early stages of development and is associated with very high energy requirement and very large amounts of material to be disposed of. Fig. 3 shows an overview of storage projects currently under way across the world.

For various reasons the storage possibilities for CO_2 are restricted at both the national and global levels. The many uncertainty factors lead to a very wide range of estimates about the extent of existing capacity, and the same applies to the question of the fundamental suitability of the various storage options, where ultimately a case-by-case analysis will be required to obtain practically relevant results.

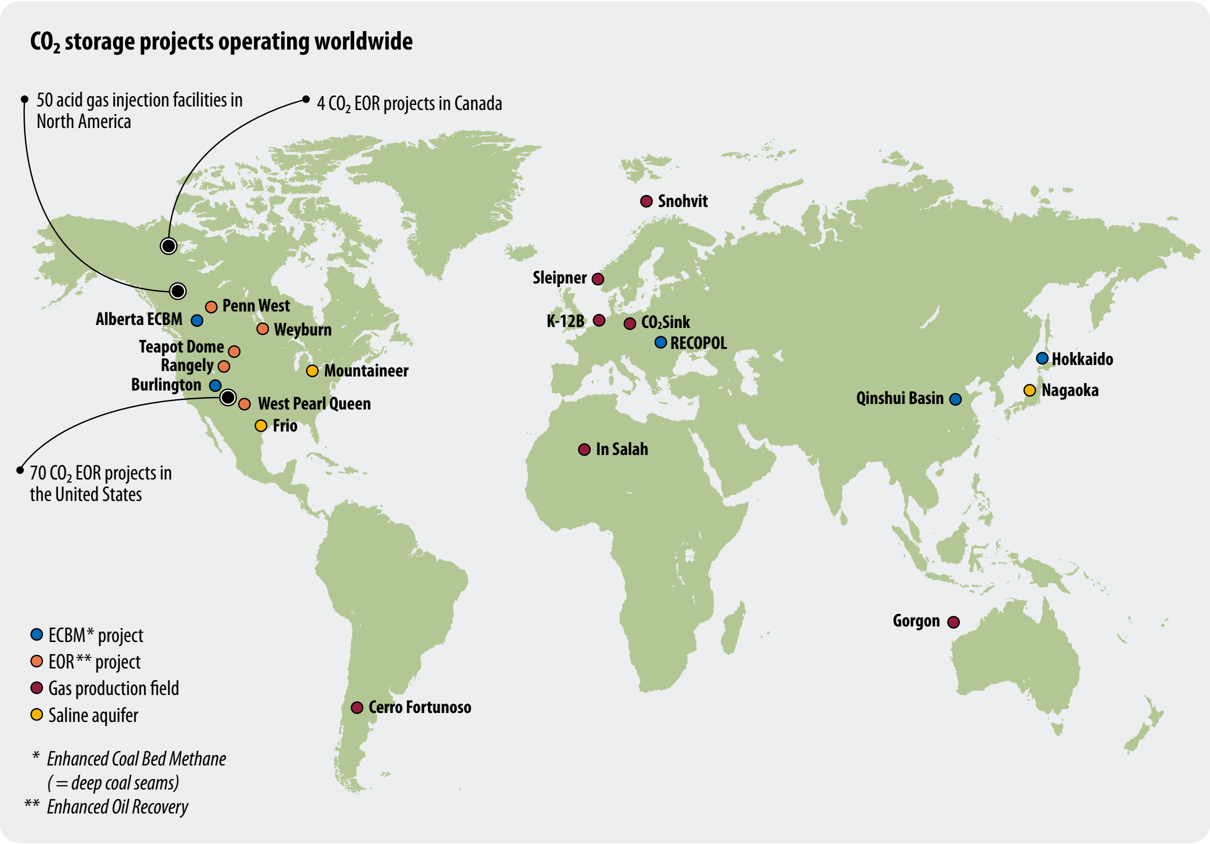

Fig. 3: CO_2 storage projects operating worldwide (IEA database)

Estimates made in 2004 put global storage potential in the range between 476 and 5,880 Gt CO_2 (with a probable potential of 1,660 Gt CO_2). By comparison, global CO_2 emissions in 2005 were 27.3 Gt CO_2. This shows that the potential of CCS is certainly considerable but that regardless of other factors, the limited storage capacity alone means that it will not be possible to achieve a lasting solution to the climate problem through CCS. Table 2 shows the storage capacity and a selection of assessment criteria, for the example of Germany.

According to current information the theoretical storage potential in Germany is between 19 and 48 Gt CO_2. The largest and – in view of the numerous as yet unresolved issues affecting storage in deep coal seams (e.g. concerning permeability) – most important share relates to deep saline aquifers, supplemented by the more limited possibilities for storage in depleted gas fields. A calculation focusing on these two storage options and taking into account an average extra energy requirement for CCS of 30 % comes up with a static range of between thirty and sixty years for CO_2 point emission sources in Germany (2005: 393 Mt/a).[1]

In principle the storage of CO_2 in geological structures can draw on many methods and technological processes currently in use in the oil and gas industry and in the disposal of liquid wastes. However, drilling and injection methods, computer simulations of the distribution of gas in reservoirs and monitoring methods will have to be adapted to the special requirements of CO_2 storage. Here there is still a great need for research and development. In Germany the EU-funded CO2SINK project will significantly increase knowledge about the behaviour and controllability of CO_2 in underground reservoirs.

Criteria for a Systematic Assessment of CCS

A systematic comparison of various CCS technologies with other technology options such as energy efficiency and renewables requires a comprehensive catalogue of criteria. The criteria used here can be categorised as follows:

Ecological criteria
- Environmental impact as per life cycle assessment (LCA)
- Energetic efficiency
- Other ecological impacts, ecological restrictions, consequences and risks (direct and indirect)

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[1] Taken together these two storage options have a potential of 14.3 to 30.5 Gt CO_2.

Table 2:
Assessment of geological storage options in Germany using selected criteria

Option	Capacity [Gt]	Long-term stability	Costs*	Available technologies	Utilisation conflicts	General risks
Depleted gas fields	+ 2.3–2.5**	+	+	+ (+)	–	+
Deep saline aquifers	+ + 12–28**	+	– –	+	–	(+)
Deep coal seams	+ (+) 3.7–16.7	+	– –	–	–	–
Depleted oil fields	– – 0,11	+	+ +	+ +	–	+
Salt caverns	– – 0.04	– –	k. A.	+	– –	– –
Disused coal mines	+ 0.78	– –	– –	– –	– –	–

* Cost estimate contains only storage costs without capture, compression or transport (after ECOFYS 2004, BGR, authors' additions)

** Figures after May et al. (2005)

Criteria:

– –	Negative or very problematic
–	Fundamental difficulties still exist, but may be resolvable
+	Good, or few obstacles
+ +	Very good
()	Parentheses indicate uncertainties or places where each individual case will have to be assessed

Economic criteria

- Generation costs and CO_2 avoidance costs (specific investment costs, resulting electricity and hydrogen production costs)

Other criteria

- Timeframe for application (possible time of implementation) and market readiness and/or R&D still required
- Compatibility with power plant replacement needs
- Acceptance
- Compatibility with existing structure and possible future development trajectories
- (Technological) stimuli for global climate protection
- Industrial policy opportunities
- Transferability to developing countries (not applicable for Germany)
- Compatibility with other climate protection strategies (decentralised options)
- Impact on import dependency
- Security policy implications

Comparative Life Cycle Assessments

For the ecological evaluation of selected system configurations (process chains from natural gas and coal to low-CO_2 electricity and hydrogen) the life cycle assessment method (LCA) defined by ISO 14.040ff was used. This integrative approach analyses the material and energy flows required to produce a kilowatt-hour of electricity or hydrogen and calculates their environmental impact.

For *electricity generation* the environmental impact of the following fossil fuel conversion paths were investigated: post-combustion (with coal- and lignite-fired thermal power plant and natural gas CC), pre-combustion (coal-fired IGCC) and oxyfuel (with coal). The Ruhr region (a densely populated industrial region in western Germany) was selected as the location of the power stations and an empty gas field 300 km away in northern Germany as the sink. For purposes of comparison with renewable energy paths, electricity generated by solar thermal power stations (in Algeria) and by wind power (in the German North Sea) was also modelled. In order to have the same reference location as with the fossil-fuelled options, the electricity was assumed to be transported to the Ruhr region using high-voltage DC lines. The following central conclusions can be drawn:

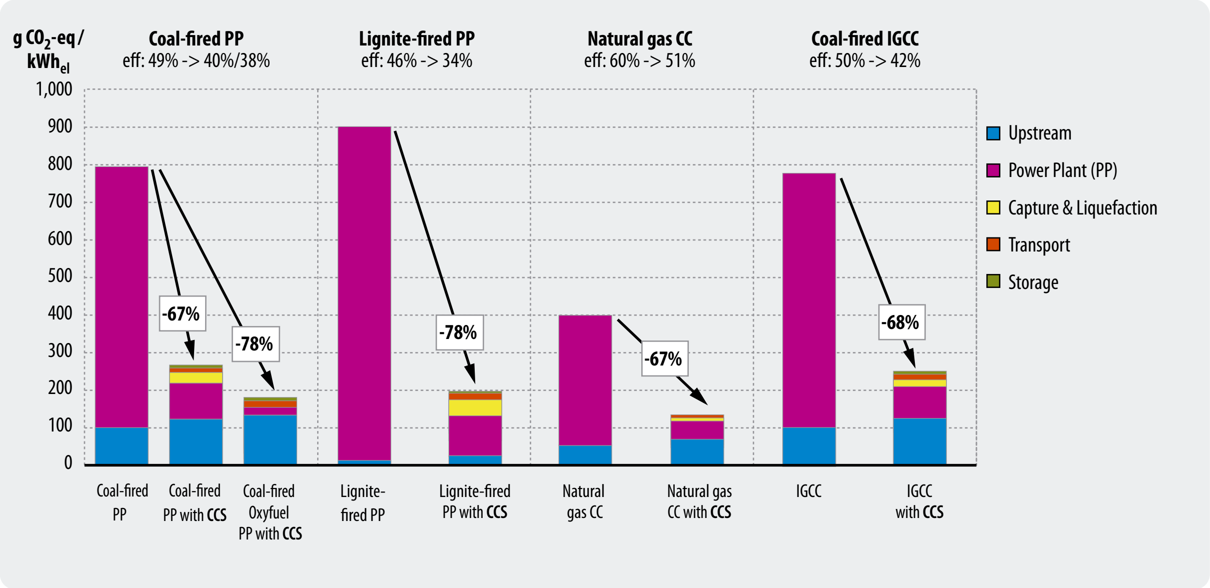

Fig. 4: LCAs of CCS plant in comparison with selected renewables (here: greenhouse gases)

The high rates of CO_2 reduction generally cited in the CCS discussion (capture rates of 88 % and more) relates only to CO_2 emissions directly in power station operation. If we take a holistic approach, 5 % of the CO_2 emissions already occur in the supply chain both with coal-fired thermal power stations and with natural gas CC. Reduced efficiency also causes higher consumption of primary energy and thus a 'larger' coal or natural gas supply chain. Taken together, these factors mean that with a capture rate of 88 % actual CO_2 emissions can not be reduced by 88 %, but only by 72–78 %. In view of this fact it is unjustified to speak of 'CO_2-free' or 'zero-carbon' power stations. Even if the capture rate at the power station can be increased still further in future, the designation 'low-CO_2' is more pertinent.[2]

The discussion to date has also neglected to consider that greenhouse gas emissions as a whole – and not only CO_2 emissions – have to be reduced. The Kyoto Protocol requires Germany, for example, to reduce a total of six greenhouse gases (and not just CO_2) by 21 % by 2012. If the effects of CO_2 capture on greenhouse gas emissions are calculated, it is found that the potential reduction is less than proportional. For example, with a CO_2 capture rate of 88 % (at the power plant) greenhouse gases as a whole can only be reduced by 67–78 % (see Fig. 4).[3] The reasons for this are again the considerably increased primary energy consumption and the methane emissions associated with fuel extraction and transport, which can be relatively high depending on the fuel and its source. Under the given assumptions these have a disproportionately large impact on the greenhouse effect. Improvements in the supply chain (e.g. collecting and using mine gas) could strongly improve the results. From a holistic perspective this lessens the reduction achievable through CCS power stations. With 396 g CO_2 equivalent per kWh the 'best' power station (in climate terms) without CCS (natural gas CC) has only 51 % more greenhouse gas emissions than the 'worst' power station with CCS (coal-fired thermal power station with 262 g CO_2 equivalent per kWh). Of all the fossil-fuelled power stations considered, oxyfuel produced the best greenhouse gas results under the given assumptions. Physical capture of almost 100 % of the CO_2 allows net rates of reduction of 90 % for CO_2 emissions and 78 % for greenhouse gas emissions.

Fig. 5 shows this in comparison with selected technologies from the field of renewables, whose impact by contrast are very small (resulting from manufacturing of the plant).

Overall, CO_2 capture requires additional energy consumption of 20 to 44 %, depending on the process. The higher energy consumption is felt directly and proportionately in various impact categories in the LCA. This applies, for example, to photo-oxidant formation, eutrophication, acidification of soil and water, and particle emissions (PM10). On the other hand, individual emissions such as SO_2, NO_2 or dust are reduced through reactions with the solvent, which in overall terms causes a reduction or at least a reduced increase in individual impact categories. Fig. 6 shows this effect for the example of the modelled lignite-fired power station (post-combustion).

The 44 % increased energy consumption initially causes a proportional increase in all impact categories. But overall the aforementioned influences cause a reduction

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[2] For example, future capture rates of up to 99.5 % are expected through the oxyfuel process. For a coal-fired power station this would result in a net CO_2 reduction of 90 %.

[3] Even with the oxyfuel method the net greenhouse gas reduction for a coal-fired power station would not be greater than 78 % (despite the higher capture rate of 99.5 %).

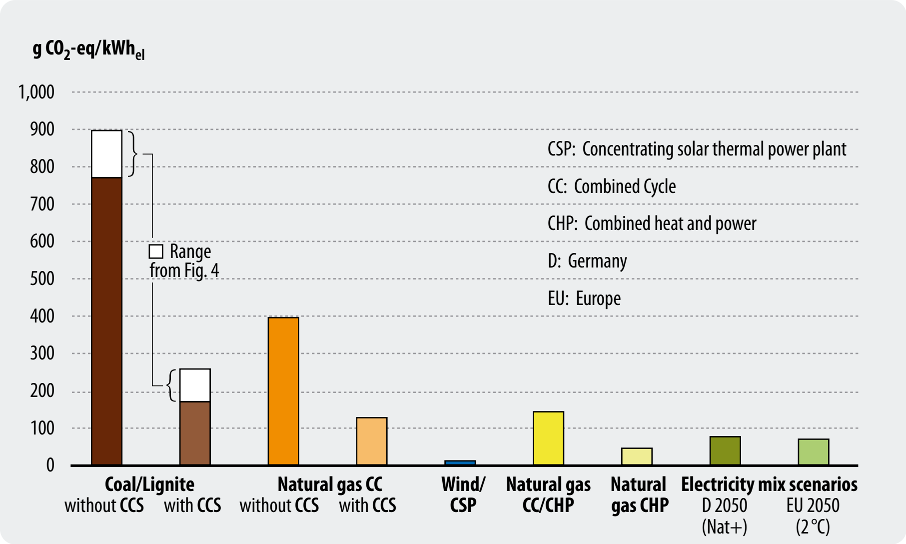

Fig. 5:
Comparison of greenhouse gas emissions from CCS power stations with selected plant from the fields of renewables and advanced fossil-fuelled CHP technologies

of 3 % in the acidification category, and PM10 equivalents rise by only approx. 24 %; on the other hand eutrophication rises by 40 % and photo-oxidant formation by 524 %.

A comparative analysis, however, showed the investigated renewable energy options to have considerably better values than the fossil-fuelled power stations with CO_2 capture. Even when electricity transmission is included, the CO_2 emissions, greenhouse gases (see Fig. 4) and cumulative energy demand of solar thermal electricity and electricity from wind power is just 2 to 3 % of the corresponding figures for fossil-fuelled CCS plant.

For *hydrogen production* the environmental impact of steam reforming of natural gas and coal gasification were investigated. The Ruhr region was again selected as the location. Renewable hydrogen production was modelled as electrolysis using electricity from solar thermal power stations in Algeria and offshore wind farms in the North Sea (as modelled for electricity generation). The location for electrolysis was the Ruhr region; again high-voltage DC lines were used for transmission. The following central conclusions can be drawn:

As with the case of power stations, we cannot speak of 'CO_2-free' production of hydrogen. It would be more pertinent to use the term 'low-CO_2' hydrogen. When the supply chain is taken into account, even with a capture rate of 88 % (coal gasification) it would only be possible to reduce CO_2 emissions by 81 %.

With natural gas steam reforming, reduction rates of only 39/52 % (CO_2 emissions, depending on different

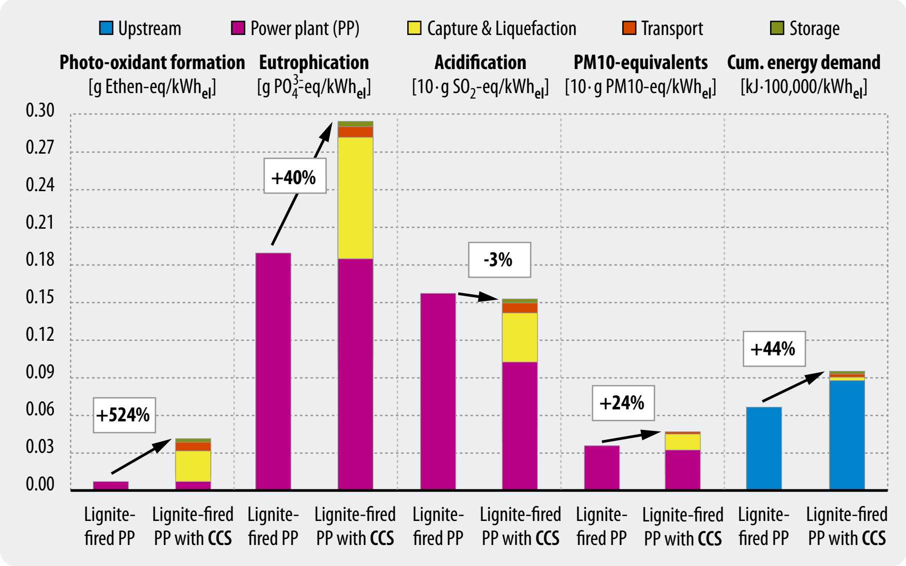

Fig. 6:
Comparison of other impact categories for lignite-fired steam power station without and with CCS (post-combustion)

reforming technologies) and 36/49 % (greenhouse gas emissions) are possible from today's perspective, if it is assumed that only the CO_2 emissions from the synthesis gas can be captured at reasonable cost, and not those that occur beforehand when natural gas is burned to produce process heat.

Other Ecological Assessment Factors for CCS

The systematic approach of the LCA does not cover every ecological criterion. As well as direct and indirect influences on the landscape (e.g. through increased fuel usage) and the negative consequences of increased transport volume through the construction of a CO_2 infrastructure, the greatest impact would result from the possibility of unplanned release of stored CO_2 and the direct influence of the stored CO_2 on the surroundings of the sink over the course of time.

The various storage options differ – in some cases considerably – in terms of ecological and safety aspects. The risk of leakage is present in all geological storage options. Whereas storage in exhausted oil and gas fields and use in oil production (enhanced oil recovery, EOR) appear relatively safe for the population and the environment, injecting CO_2 into disused coal seams could pose considerably greater risks. Saline aquifers are regarded as relatively stable long-term sinks, although there is still a great need for research into the underground movement of CO_2 (mechanisms of dissemination and activity). Such aquifers have so far generally only been explored in the vicinity of hydrocarbon deposits so there is a shortage of comprehensive data and assessments of their petrophysical properties. The introduction of CO_2 leads to acidification of the water in the aquifer. Through its corrosive properties the acidic water could cause changes to the surrounding strata (especially carbonates) and to unprotected borehole seals.

The use of deep (currently uneconomic) coal seams bears the ecological risk of the extracted methane escaping (methane is a considerably more potent greenhouse gas than CO_2, by a factor of 21).

Marine storage options are associated with very great uncertainties and risks. Direct cause and effect relationships have so far only been demonstrated in certain cases. Acidification of seawater shifts the carbonate equilibrium: the shells of calcifying organisms become thinner and can even dissolve, interrupting food chains or at least altering them with inestimable consequences. CO_2 lakes on the ocean floor affect more than the local ecosystems. Many aspects of the behaviour of the ocean floor – submarine slides, undersea quakes, etc. – may be understood, but they remain unpredictable. Fundamentally it must be noted that storage in the oceans would not lead to permanent sequestration of the CO_2. Dissolving CO_2 in the ocean depths leads to delayed re-emission into the atmosphere after a few hundred years at the latest, when oceanic circulation brings the water masses into contact with the atmosphere again. In view of the unclarified consequences of marine storage options they are categorically rejected by the environmental organisations and are being pursued in any form in only a very few countries (in particular Japan).

Fixing CO_2 in biomass by planting forests and growing monocultures brings with it multifarious ecological problems. It must also be emphasised that this form of storage is only a temporary one, with delayed release. When a period of several generations is considered, the reduction effect is nil. Additionally, monocultures displace other species and alter biotopes.

The construction and operation of renewable energy technologies – e.g. constructing wind farms, hydroelectric dams and solar thermal power stations – can in certain cases be associated with considerable ecological consequences and disfiguration of the landscape. Within a social and energy system guided by sustainability principles, decisions would have to be made about which interventions are acceptable for the population and the natural environment and which should be avoided. Whereas the impact of using renewables is largely known and understood, decision-making with respect to CCS is from today's perspective still hampered by numerous uncertainties and open questions.

Economic Comparison of CCS and Renewables

If the capture and storage of CO_2 emissions from fossil-fuelled power stations can be demonstrated successfully, electricity generating costs (at power station) of between 6.5 and 7 ct/kWh can be expected on the basis of CCS power stations commercially available in 2020 (interest rate 10 %/a). In view of the fuel price rises expected in the longer term, a further rise in costs to between 7 ct/kWh (coal) and 8 ct/kWh (natural gas) is probable by 2040. In coal-fired power stations the fuel price effects could potentially be largely balanced out by further technical progress. Our calculations put CO_2 avoidance costs at between €35 and €50/t CO_2 in 2020, when the same power station without CCS is taken as the reference for comparison. Here coal-fired power stations are towards the bottom end of the range, gas-fired towards the top. This is less than the cost range assumed today and assumes that significant learning processes will already have occurred by then, but is still significantly higher than the costs of about €20/t CO_2 that the energy business is aiming at for the process as a whole.

Renewables, which – on the basis of a representative mix – today still involve electricity generating costs of approx. 13 to 14 ct/kWh (again assuming interest rate 10 %/a) can also achieve that level of costs by 2020 if their market introduction continues at a similar pace to now. With a continuing global increase in market penetration and learning effects significant cost degres-

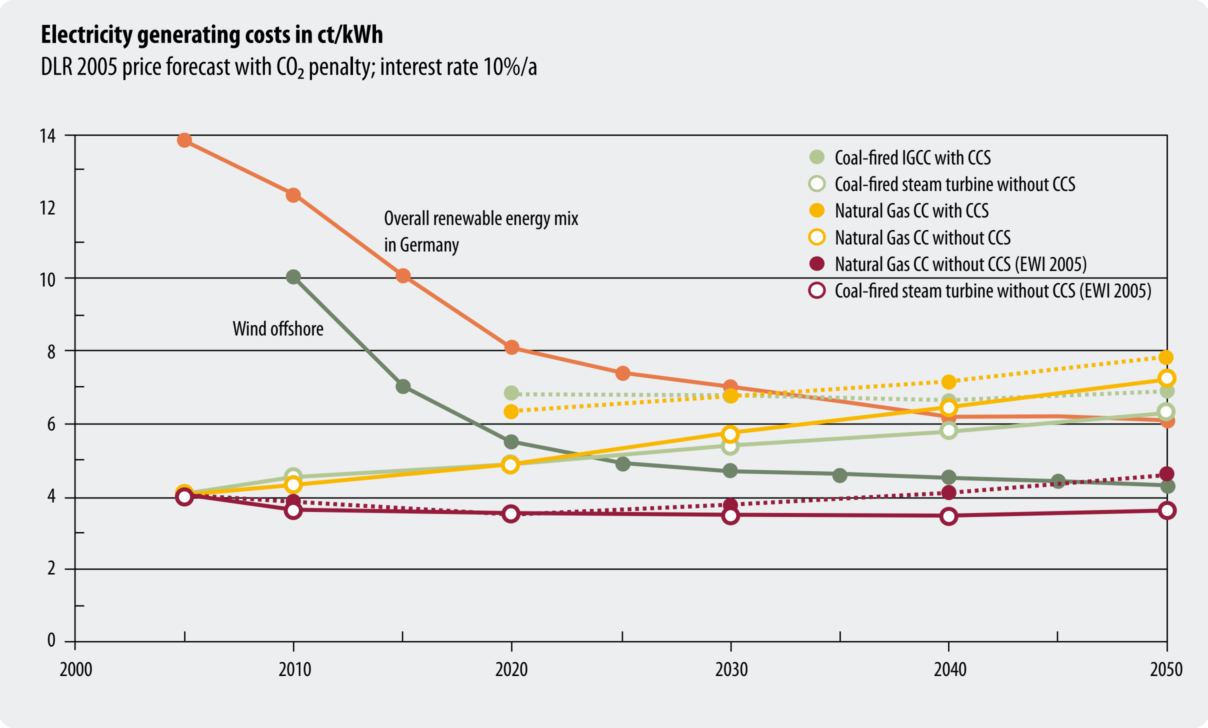

Fig. 7: Development of electricity generation costs (for new plant) for renewables, conventional gas- and coal-fired power stations and CCS power stations. Fuel prices after "DLR 2005" and for conventional power stations without CCS after EWI 2005 given for comparison

sions can still be expected for renewables in future, so that by 2050 the level of costs for generating electricity from renewables in the characteristic mix under consideration could fall to 6 ct/kWh. Individual technologies could achieve electricity costs of approx. 4 ct/kWh if a continuing expansion of global markets allows the learning curve to continue to be exploited (see Fig. 7).

If the pace of expansion of renewables in the electricity sector remains fast – as in the various scenarios that describe a switch to a climate-friendly energy supply based on a combination of stepping up the expansion of renewables and energy efficiency (e.g. the Naturschutzplus scenario) – at the time when the first CCS power stations might be coming on stream some technologies (e.g. wind offshore) could already be offering cheaper electricity generation costs and further increase that advantage over the course of time. Here significant cost-reduction effects come through the global market effects, so even if renewables in Germany were to grow less dynamically, cost parity between CCS and individual renewables can be expected. Only if fuel price rises were to be very small or cost reductions in the CCS process were to surpass the foreseeable effects would the situation be more favourable for CCS plant. This would not negate the general effect, but would push back the point on the time axis where renewables become relatively competitive.

Under the given assumptions there is neither a compelling economic reason to give CCS technologies preference over a further expansion of renewables for electricity generation. Nor, though, do they represent a prohibitively expensive option and if successfully commercialised under suitable conditions (inexpensive, stable long-term storage options, good infrastructure, cheap coal) could become part of the future electricity generating regime in some world regions.

In an economic comparison of low-CO_2 and largely CO_2-free options for hydrogen production (CCS versus renewables) the fossil option comes off best. By 2020 hydrogen from coal gasification with CO_2 capture will cost approx. €12.50/GJ (4.50 ct/kWh, upper heating value, at plant), or about twice the cost of today's hydrogen from natural gas reforming. Further fuel price rises until 2050 increase the cost to about €14/GJ (5.04 ct/kWh). Only electrolytic hydrogen via electricity from cheap hydropower can compete with this, but the available capacity is small. Only in the longer term costs of around €16–18/GJ for electrolytic hydrogen from wind or solar electricity can be expected; around 2020 the cost will probably be about €19–20/GJ. In the medium term the cost of generating hydrogen will always be at least double the cost of natural gas. So for economic reasons hydrogen will not be implemented as a fuel before 2030. Regardless of the way it is produced, it will probably be several decades before hydrogen becomes important in the energy sector in relevant quantities because of the considerable infrastructure challenges associated with its introduction.

The Role of CCS in Industrialised Countries – the Example of the German Energy Supply System

In this study three different scenarios were developed for the future energy supply in Germany (as a representative industrialised country) in order to analyse the role of CCS in the energy sector in comparison to renewables. In all three scenarios energy-related CO_2 emissions were reduced to 240 million t/a by 2050, which corresponds to a reduction of about 75 % compared with 1990. The **scenarios** are based on the following assumptions:

- **CCSMAX**: CCS as the main element of a climate protection strategy with 'maximum' use of CCS technologies within the framework of a development that otherwise largely follows current trends for energy consumption and expansion of renewables (relatively small mobilisation of efficiency potentials, limited implementation of the expansion potentials of renewables).

- **NATP**: Concentration on across-the-board exploitation of energy saving potentials and vigorous expansion of renewable energy technologies, as described in the 'NaturschutzPlus' scenarios prepared for the Federal Environment Ministry (after BMU 2004 and BMU 2005). In this scenario CCS is not required.

- **BRIDGE**: CCS as a bridge to further expansion of renewables while at the same time increasing energy efficiency and expanding renewables more strongly than in the reference case but less than in NATP. In this scenario the two strategy elements are insufficient to achieve the climate target unaided, so the use of CCS is required.

Various key findings can be drawn from the scenario analyses. Emission-reducing measures in the field of electricity generation alone will simply not be enough to meet the climate protection target. Similarly comprehensive measures in the heating and vehicle fuel sectors are also required. As well as expanding renewables, the exploitation of efficiency potential will have to make a very considerable contribution. If greater use is made of fossil resources, the alternative of generating hydrogen by gasifying coal with carbon capture and storage is always an option.

As the main element of a climate protection strategy CCS runs into structural and capacity limits (**CCSMAX scenario**). The earliest date when CCS technologies are expected to be ready for implementation is 2020, which is too late for the first wave of the power station replacement needs, which has just begun. This scenario would necessitate extremely rapid growth rates for CCS plant between 2020 and 2050 and speedy establishment of a hydrogen infrastructure. With 5,900 PJ/a the demand for coal in CCSMAX rises to three times today's level. By 2050 hydrogen would be the dominant form of energy, supplying 47 % of final demand. The amount of CO_2 to be captured and stored in 2050 would amount to about 600 million t CO_2/a (Fig. 8). At that level the storage capacity available in Germany would last for just one or two decades. Cost advantages for energy produced using CCS are either non-existent (for electricity) or marginal (for hydrogen) so there is no decisive economic incentive for such a prominent preference for CCS. The high level of funding already required today in the form of R&D and demonstration plant for such a strong expansion of CCS technologies would probably demand a major turn away from support for efficiency strategies and strategies for expanding renewables. A great challenge in view of the very many questions that are still open is that the lead times involved mean that it would be necessary relatively quickly to achieve a very high level of certainty about the ecological impact and long-term stability of the potential CO_2 sinks.

A climate protection strategy following the **NATP** scenario, which manages without CCS, would not yet develop of its own accord. As well as maintaining the current dynamic rate of expansion of renewables in the electricity sector and extending their use to the heat sector on a significant scale, considerable additional support measures to encourage much greater efficiency in use and conversion of energy would be required if the 2050 climate protection target is to be met on time by this strategy. Expanding renewables and increasing efficiency are measures that take effect relatively quickly, so as long as the necessary support measures impact fast, they allow the restructuring process to run more harmoniously than in the CCSMAX case described above. Major conversion of energy infrastructures would be required, but this could be realised in stages. A strategy concentrating especially on energy productivity also makes sense in broader economic terms because many of the efficiency measures represent the most economic option for climate protection regardless of what measures are taken on the supply side. If external costs were included the overall economic situation would be even more favourable. To that extent this scenario represents an 'ideal strategy' but one which demands that very effective energy policy decisions be taken quickly, especially a clear rationalisation and expansion of energy efficiency policy. In the longer term this scenario necessitates considerable structural changes, increasing the network and system integration of renewables on the electricity side, integrating energy import structures (e.g. electricity from solar thermal power plant in North Africa) and greatly expanding district heating systems.

To pursue both strategies 'at full steam' until 2020 (efficiency and expansion of renewables following NATP until 2020; CCS development as in CCSMAX), but then to largely drop one of the options would not seem to be a sensible way to proceed. Consequently, the third scenario discusses the extent to which the two strategies could be combined compatibly in a forward-looking strategy.

In a development corresponding with the **BRIDGE scenario** the timeframe for introducing CCS technologies and a hydrogen infrastructure is more relaxed than in CCSMAX because until 2030 the contribution required

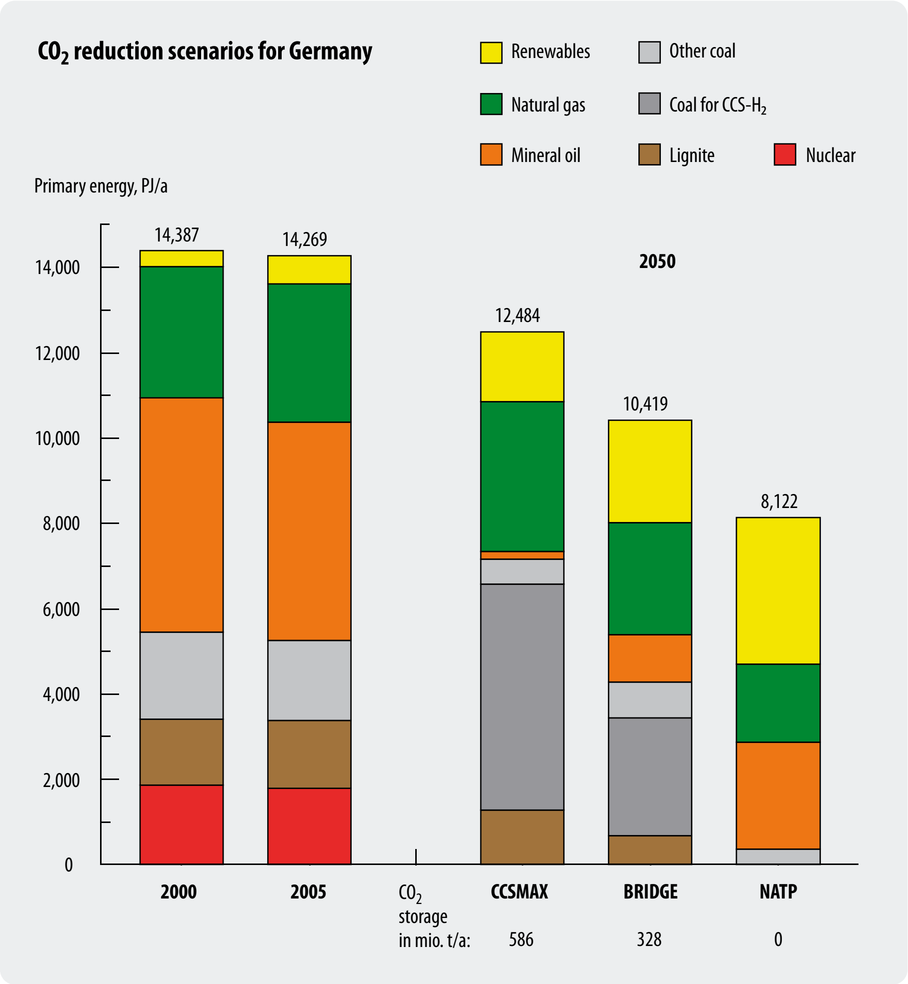

Fig. 8:
Primary energy structure today and in the scenarios for 2050

from this option can remain relatively small. In the event that CCS technologies turn out to be a sensible and ecologically sustainable energy option, even the level of expansion required by 2050 does not encounter any fundamental barriers concerning required plant capacity, infrastructure modifications or sink capacity. In this case about 330 million t CO_2/a would have to be captured and stored in 2050. For this, however, fossil-fuelled power stations built before 2020 must also be suitable for retrofitting with CCS, if the electricity sector is to make a substantial contribution to reducing CO_2. This should be taken into account in current ongoing power station planning, and where possible plant should be designed to be 'capture ready'.

An energy policy following the BRIDGE strategy will definitely demand a general intensification of energy policy in all the listed fields if long-term climate protection goals are seriously to be achieved. So including 'CCS technologies' as an additional climate protection option should not serve as an excuse for neglecting the strategy elements of 'energy efficiency' and 'renewables' as the process intensifies. Instead these should be mobilised by 2020 at least to the extent that they can continue to 'take off' thereafter if CCS technologies should turn out to be unworkable on the desired scale in the energy sector. At the same time, this timeframe offers the opportunity to explore the development and cost potentials of CCS technologies thoroughly and without massive pressure of time. But the successive introduction of CCS could help as an ancillary element to make it easier to maintain the sustained impetus for further efficiency increases and a greater expansion of renewables than would possibly be the case with the significantly higher hurdles in the NATP scenario. This could identify ways to soften resistance and to offset obstacles that remain insurmountable despite massive support and energy policy intervention. In view of the real constellations of interests and different evaluations of technology options in the field of energy, especially in the global context, a development following the BRIDGE scenario can be regarded as a 'pragmatic' strategy.

A cost comparison of renewables and CCS technologies for electricity and hydrogen production shows no economic advantages for the CCS option at the point of its possible introduction around 2020. The latter would then require CO_2 prices between €40 and €50/t CO_2 if it is to be attractive to private investors in place of conventional electricity generation from fossil fuels. Even after 2020 renewable energy technologies will probably continue to have exploitable cost degression potentials, whereas the cost of generating electricity from coal with CCS will probably remain roughly constant, assuming a corresponding degree of technical development. If we factor in the external costs, we find further advantages for the development path building on renewables and energy efficiency. From today's perspective, the relative profitability of CCS and renewables is associated with diverse imponderables. The above assessments for renewables work on an assumption of dynamic global market developments allowing very considerable cost degression potentials to be exploited via mass production and learning curve effects.

One obstacle to a comprehensive CCS strategy could also be that a strategy building largely on CCS would require the earlier introduction of (low-CO_2) hydrogen on a broad scale, which is associated with great infrastructure challenges, whereas a strategy orientated on NATP would not require this on an appreciable scale until the middle of the century.

From the aforementioned aspects it follows that a rigorous strategy based on the NATP scenario could also represent the more favourable option in broader economic terms in the medium to long term and should thus be the aim of energy policy. At the same time, it would be recommendable to continue to subject the CCS option to thorough scrutiny and in particular a realistic practical demonstration, in order to possess after a decade more precise knowledge of the potential and limits of this set of technologies. If it then turned out that in terms of efficiency and expanding renewables the restructuring of the global energy supply can 'only' proceed at the intensity described in BRIDGE, then CCS would be available as an additional climate protection option.

Requirements for Successful International Implementation of CCS

The concluding part of the study broadens the perspective to examine whether CCS is necessary from a global perspective in order to meet ambitious climate protection targets and how an institutional framework can be established to sensibly regulate the risks of CCS.

The role of CCS in the context of other technology options – i.e. in particular the expansion of renewables – was analysed by means of an economic scenario analysis. Models to maximise global social welfare for a given limitation of the atmospheric CO_2 concentration were chosen by simulating the progress over time of implementation of the three named options (and in the process including the technological learning effects). Central uncertainty factors that have a strong influence on the implementation of CCS and on the costs of climate protection were identified and interpreted by means of sensitivity analyses:

- Learning rates for CCS and renewables influence the cost reduction curve of the technologies and thus their application. The quicker the cost-cutting potential of renewables is realised and the slower that of CCS takes effect, the less CCS will be used. However, in both fields of technology as yet unforeseeable development leaps and costs that cannot be reduced through learning effects (e.g. for fuels) could have a strong influence on their respective future market shares.

- Leakage rates (quantifying the slow escape of CO_2 from storage formations) must be well below 0.1 % per year if CCS is to be used efficiently at all.

- The discount rate determines the weighting of consumption over the course of the planning period. If a high discount rate is chosen – giving welfare in the present a higher weight and consequently resulting in less being invested in renewables – CCS gains and greater use of renewables is shifted back to a later date. This occurs above all when realising learning rates in renewables requires high initial investment compared with CCS.

- The rising cost of exploration and extraction associated with possible shortages of fossil resources has a strong effect on the role of CCS. Because of the attractiveness of fossil fuels, if their costs of do not rise until relatively late, CCS will be used extensively in order to meet the set climate protection target at all. But under 'peak oil' scenarios, which predict rapidly rising costs due to depletion of oil reserves, the substitution of various fossil fuels could occur considerably earlier, which would reduce the demand for CCS. However, the timeframe and interrelationships of these effects are not yet fully understood.

- The use of CCS is worthwhile even if the time when CCS technologies become available for large-scale application is delayed by several decades. But if CCS were not available until 2050 the amount of CO_2 stored to meet climate protection targets would be reduced considerably because it would then be more worthwhile to step up implementation of renewables from the outset.

The outcome of the economic scenario analysis is that at the global level CCS can make a tangible contribution to meeting ambitious climate protection targets. CCS can fulfil a 'bridging function' of avoiding emissions on a scale that renewables and efficiency improvements cannot achieve on their own, and in that context the two technology options can complement one another. There can be no doubt, however, that in the long term a sustainable reduction of climate change is achievable in the energy sector only through renewables and high energy efficiency.

Overall, according to the calculations, keeping the atmospheric concentration of CO_2 below 450 ppm over the course of the twenty-first century could be achieved with a relative loss of 0.6 % of global GDP compared with the business-as-usual trajectory, in the process of which a total of approx. 456 GtC (or 1,672 Gt CO_2) would have to be captured and stored. These results should be understood as plausible mid-range figures – assuming a leakage rate of 0.05 % per year and a learning rate for renewables of 15 %. The precise figure for cumulative storage and the cost reduction will depend on the development of the investigated uncertainty factors. The model calculations show that with a combination of both measures (renewables plus increased efficiency *and* CCS) it would be possible to achieve ambitious global climate protection targets at a relatively small loss of economic growth. The calculated growth losses are relativised still further if the necessary investments in measures for adapting to climate change are factored in.

Large-scale introduction of CCS presumes the implementation of an institutional framework that sensibly regulates the risks of CCS and offers incentives to use the safest possible storage options.

Many details of the national and international legal situation have yet to be clarified, and special frameworks for CCS have yet to be developed. In view of the long-term nature of CO_2 storage, the principles of environmental law require legislators to ensure there are suitable rules for dealing with future risks and to strike a suitable balance between business liability for harm caused and the ultimate responsibility of the state. Monitoring sinks and defining an appropriate leakage rate are particularly important here. Because of the transfrontier effects of CCS, international agreements are imperative.

As the economic analysis showed, it makes sense to embed CCS in international climate protection agreements. However, CCS is not yet included in the mechanisms of the UN Framework Convention on Climate Change. Guidelines for accounting for the emissions saved through CCS (and those that may be released again) have not yet been implemented. That would be an important precondition for being able to include CCS in the flexible mechanisms of the Framework Convention on Climate Change. With regard to the debate between the two fundamental approaches to climate protection agreements (cap and trade system and technology protocol) CCS, with its technological challenges that are yet to be mastered, could serve to illustrate that both approaches are possible and useful.

Regulating responsibility for risks from CCS could be achieved through tradable **carbon sequestration bonds,** which the operator of a CCS project would be obliged to purchase and which would be depreciated proportionately if leakage occurs. The bond system offers incentives for efficient limitation of harm caused by CO_2 leakage and involves the financial markets and through them the public (via investment decisions for safe CCS projects) in the control of risks. State revenues through devaluation of bonds could be used to promote renewables, thus balancing out the delay in their development resulting from the use of an unsafe storage option.

Structure of Long Version

The long version has 226 pages, 60 tables and 116 figures. It can be obtained as paper version and electronically at www.bmu.de.

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