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Comparison of Renewable Energy Technologies with Carbon Dioxide Capture and Storage (CCS)

Update and Expansion of the RECCS Study

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Final Report

to the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU)
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Wuppertal Institute
Dipl.-Umweltwiss. Andrea Esken
Dipl.-Umweltwiss. Samuel Höller
Dr. Hans-Jochen Luhmann
Dipl. Soz.-Wiss. Katja Pietzner
Dr. Daniel Vallentin
Dr. Peter Viebahn (Project Leader)

With subcontracts to
Dr. Lars Dietrich LL.M. (Sozietät Wolter Hoppenberg, Hamm)
Dr. Joachim Nitsch (Stuttgart)
Translation
Teresa Gehrs (Europäischer Sprachendienst, Osnabrück)

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Final Report

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Contact

Dr. Peter Viebahn
Research Group “Future Energy and Mobility Structures”
Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19
42103 Wuppertal
Germany
Tel.: +49 (0)202 2492-306
Fax: +49 (0)202 2492-198
E-mail: peter.viebahn@wupperinst.org
Web: www.wupperinst.org/CCS/

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List of abbreviations and symbols

Abbreviations

AEP	American Electric Power
AOSIS	Alliance of Small Island States
BGR	Federal Institute for Geosciences and Natural Resources (*Bundesanstalt für Geowissenschaften und Rohstoffe*)
BMBF	German Federal Ministry of Education and Research
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMWi	German Federal Ministry of Economics and Technology
CAGS	China-Australia Geological Storage
CAR	Ceramic Autothermal Recovery
CCS	Carbon (Dioxide) Capture and Storage
CCSA	Carbon Capture & Storage Association
CCSD	Cooperative Research Centre for Coal in Sustainable Development (AUS)
CDM	Clean Development Mechanism
CER	Certified Emissions Reductions
CHPG	Combined Heat and Power Generation
CHPP	Combined Heat and Power Plant
CLC	Chemical Looping Combustion
CLSF	Carbon Sequestration Leadership Forum
CO	Carbon monoxide
CO_2	Carbon dioxide
CO2CRC	Cooperative Research Centre for Greenhouse Gas Technologies (AUS)
COACH	Cooperation within CCS China-EU
COM	Communication measure of the European Union
COORETEC	“CO2 REduction TEChnologies” initiative
COP	Conference of the Parties (UN)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DOE	U.S. Department of Energy
EB	Executive Board
ECRA	European Cement Research Academy
EEPR	European Energy Programme for Recovery
EGR	Enhanced Gas Recovery
EIA	Environmental Impact Assessment
ENCAP	Enhanced Capture of CO_2
ENVI	The Environment, Public Health and Food Safety Committee (EU)
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency (USA)
EPRI	Electric Power Research Institute

ETS	Emission Trading System (EU)
EU	European Union
FP	Framework Programme
GGGSA	Greenhouse Geological Sequestration Act 2008 (AUS)
GHGT	International Conference on Greenhouse Gas Control Technologies
H2	Hydrogen
HR	House of Representatives, USA
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
IPPC	Integrated Pollution and Prevention Control
ITM	Ion Transport Membrane
IZ Klima	*Initiative Klimafreundliches Kohlekraftwerk* (climate-friendly coal-fired power station initiative)
JCG	Australia-China Joint Coordination Group on Clean Coal Technologies
LCA	Life Cycle Assessment
LCP	Large Combustion Plants
LDC	Least Developed Countries
LPG	Liquefied Petroleum Gas
MEA	Monoethanolamine
MOP	Meeting of the Parties (UN)
NGCC	Natural Gas Combined Cycle
NGO	Non-Governmental Organisation
NRW	North Rhine-Westphalia
NZEC	Near-Zero Emission Coal Technologies (China)
OJ	Official Journal of the European Communities
OSPAR	International Cooperation on the Protection of the Marine Environment of the North-East Atlantic
OTM	Oxygen Transport Membrane
R&D	Research & Development
RMB	Renminbi (currency of the People's Republic of China)
RTI	Research Triangle Institute
SBSTA	Subsidiary Body for Scientific and Technology Advice
SCCS	Scottish Centre for Carbon Storage
STP	Steam Power Plant
STRA-CO2	Support to Regulatory Activities for Carbon Capture and Storage
TGR-BF	Top Gas Recycling-Blast Furnace
UBA	German Federal Environment Agency
ULCOS	Ultra Low CO_2 Steelmaking
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
VO	European Community Regulation
WI	Institute for Climate, Environment and Energy
WRI	Western Research Institute

Units and symbols

°C	degree Celsius
a	annum
A$	Australian dollar
b	barrel
B_g	gas expansion factor
c_p	compressibility of pores or rock
c_W	compressibility of formation water
E	efficiency factor
E_d	displacement efficiency
el	electric
E_V	volumetric efficiency
FVF	formation volume factor
g	gram
Gt	gigatonne (1 billion tonnes)
h	hour
K	Kelvin
kWh_{el}	kilowatt hour electric
kWh_{th}	kilowatt hour thermal
l	litre
m	metre
$m_{CO2,\ effective}$	effective gravimetric storage capacity
$m_{CO2,\ theoretical}$	theoretical gravimetric storage capacity
MJ	mega joule (0.278 kWh)
MPa	mega Pascal
Mt	megatonne (1 million tonnes)
MWh	megawatt hours (1,000 kWh)
n/g	net-to-gross ratio (proportion of sediment structures with porosity and permeability suitable for absorbing CO_2)
th	thermal
traps%	proportion of traps in the total volume
TWh	terrawatt hour (1 billion kWh)
US$	United States dollar
V_b	volume of the potential storage
V_{gas}(STP)	cumulative production volume under standard conditions
ρ_{CO2}	density of CO_2
ϕ	porosity

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Conclusive hypotheses

Global development of CCS between 2007 and 2009

- A brief glimpse at the worldwide development of CCS over the past three years shows that the development and demonstration of CCS has been given an increasingly high profile in Germany, the European Union and many other countries (China, the USA and Australia have also been analysed).
- Throughout Europe, 41 pilot and demonstration projects were set up in the power plant sector. The majority of these took place in England, the Netherlands and Norway, followed by Germany. Additionally, CO_2 capture is being explored in eight known projects within other industrial sectors.
- Internationally, the integration of CCS in the Clean Development Mechanism (CDM) remains highly controversial. The contentious issues in the negotiations are not only the basic questions about the suitability of CCS as a technology to reduce greenhouse gases; there are also complex methodological and legal problems.
- According to the latest industry publications and press releases, the entire CCS chain (separation, transportation and storage) is only expected to be available on a commercial scale from between 2025 and 2030.

Process of CO_2 separation in electricity generation

- Numerous capture processes are being developed worldwide within the individual technological routes.
- The majority of the research projects are being carried out in the post-combustion process, where there are also the most suppliers. Despite the fact that post-combustion technology is the least efficient of these processes, research into it has been prioritised with a view to potentially retrofitting power stations.
- In addition to a variety of capture processes within the absorption, adsorption and membrane methods, biological processes are gaining increasing attention (using algae or enzymes).

Options for the use of CO_2

- Carbon dioxide can be reused, in particular as a parent substance to produce a variety of materials, ranging from the chemical raw material methanol to end products, such as urethane, tensides and urea. It can also be used in dry cleaning, fire extinguishers, cooling units and aerosol cans.
- Previous estimates assumed, however, that between much less than 1 per cent and a maximum of 5 per cent of the current quantity of CO_2 produced can be bound to product cycles.
- There are also a number of ideas for applying biological processes to use CO_2 to create algae biomass, which can be further utilised to produce biogas, biodiesel, bioethanol or biohydrogen.

Driving forces and attitudes of relevant stakeholders

- Since 2007, the number of stakeholders involved in the public debate on CCS has steadily grown.
- The opinions of environmental and climate protection organisations, relevant industry associations and trade unions, representatives of religious institutions, parties represented in the Bundestag, federal state governments, advisory committees to the German government and research institutions were examined. Between them, they represent a wide range of views on CCS.
- The topics on CCS technologies currently being debated are much more specific. In 2007, discussions focused mainly on the technical and economic feasibility of the technology. Now there is a much broader and frank discussion on the topic, involving advanced aspects such as potential competitive usages with other technologies and liability issues.
- Now, the interest in CCS is not limited to its context in coal-fired power plant technologies. Industrial applications of the technology are also becoming an increasingly important option for reducing process emissions, as well as its relationship with the use of biomass.
- One specific aspect of this debate, however, remains constant: the opinions and attitudes on the subject of CCS are highly divided between its supporters and opponents, even within the same groups of stakeholders.

Legal aspects of introducing CCS to power plant technology

- In June 2009, the EU adopted the CCS Directive (2009/31/EC), which is to be transposed into the national law of all Member States within two years. This Directive, along with other modified legal acts, constitutes a comprehensive regime for the use of CCS technology valid in all EU Member States that is suitable for achieving the stated objectives.
- By integrating the entire CCS process chain into the European emission trading scheme, a mechanism will be activated so CCS can be used to provide incentives to investors both in terms of safety and business management.
- The applicable German law has been inadequate for coping with the different procedural steps of the CCS chain. Here, the major problems arise in the field of CO_2 storage, solely aimed at permanently removing CO_2. For this reason, plans concerning the permanent storage of CO_2 are only permitted in a few constellations in accordance with the applicable law.
- In view of the current gaps in knowledge, a CCS law should initially facilitate only R&D and demonstration plans, and then be reviewed. A suitable legal framework for this, however, is necessary in the short term.
- Neither the Directive nor the German draft law stipulates how to resolve cases where competing projects require the same geological formation in order to be realised (for example, geothermics or gas storage versus CO_2 storage). Therefore, regulations should

be devised to capture, assess and solve such conflicts of use resulting from the large-scale use of the CCS process.

Analysis of the options for storing CO_2

- The aim of this analysis was a) to systematically analyse and compare the existing capacity estimates for storage sites regarding their methods and assumptions, and b) to present a cautious, conservative estimate as a lower limit for planning purposes for potential investors and political decision-makers, not only for Germany but also its neighbouring countries where CO_2 emissions from Germany could possibly be stored.
- Using a scenario analysis, a typical "what-if" examination was conducted in which cautious estimates and assumptions were pooled. The analysis is not based on new geological data, but instead uses the findings available in the literature.
- The cautious, conservative estimate calculates an effective storage potential for Germany in the region of 5 billion tonnes of CO_2 (on the basis of closed systems and the resulting efficiency factor of 0.1 per cent for saline aquifers). The fluctuation range yields values between 4 and 15 billion tonnes of CO_2.
- The storage potential would be sufficient for emissions in Germany, computed to be 1.2 billion tonnes of CO_2 up to 2050 in the "realistic" power plant scenario.
- The effective conservative capacity estimated for north-western Europe is 49 billion tonnes of CO_2. This capacity would be enough to store the current emissions from large point sources for the next 40 years.
- These estimates, however, do not consider a geographic comparison of sources and sinks, suitable transport infrastructure, legal issues or questions concerning public acceptance.
- At present, all estimates of storage capacities should generally be treated with caution.
- Enhanced oil recovery (EOR) could act as an initial scenario for CCS in Europe if sufficient CO_2 is made available by 2020. However, EOR needs to first prove itself offshore.
- Since EOR does not assist with climate protection, coupling CCS to this technology is at odds with the goal of reducing global greenhouse gases.

Environmental assessment of CCS compared to renewable energies

- CO_2 capture requires a much greater consumption of finite resources, with all associated consequences.
- Taking into consideration this increased consumption and the entire process chain, including the upstream processes of substances and energies used, the greenhouse gas emissions from CCS power plants that will start operating in 2020 can be reduced in total by between 68 and 87 per cent (in exceptional cases up to 95 per cent).
- Due to the increased consumption of energy, there will be an effect on many other environmental impacts. In some cases, this will be considerable (and can only be reduced significantly by pure oxygen combustion).
- The recommendations by some authors to install a comprehensive monitoring programme for the first CCS power plants should be taken seriously. This way, we can gain

information about the actual emissions caused or reduced by the capture. Such information would considerably improve our understanding of the individual chemical processes, and how to model them.

- Even compared with CCS power plants, renewable energies are responsible for only a fraction of greenhouse gas emissions. In 2025 (2050), offshore wind will cause only 5 to 8 (9 to 15) per cent, solar thermal energy 11 to 18 (13 to 23) per cent and photovoltaics 14 to 24 (7 to 12) per cent of emissions from CCS power plants. All renewable energies will have improved in absolute terms by 2050, but show higher percentages, with the exception of photovoltaics, because CCS technologies will also improve.
- Other aspects have also been neglected in life cycle assessments. These include drastic, extensive changes to the landscape caused by coal mining, the consequences of a lowering of the ground water table, contamination of the water by mine drainage and the creation of enormous slag heaps that have a negative impact on groundwater supply for agriculture and the surrounding ecosystems.
- It is not yet apparent whether the transportation of large quantities of carbon dioxide will have a bio-geo-chemical impact on the microbial biota in deep rock formations.

Economic comparison of CCS power plants and renewable energy technologies

- According to the calculations presented here, electricity generating costs incurred by CCS power plants of between 7.30 and 10.35 ct/kWh$_{el}$ (at power plant) can be expected by 2020 (assumed real interest rate 6 per cent per annum). In addition to expenditure for power plants, the development of fuel and CO_2 allowance prices until 2020 have been taken into account. Usage fees for storage sites, (“storage fees”), have not yet been included in the calculations.
- If the dynamics of the expansion of renewables in the electricity sector remain high, it is possible that individual renewable energy technologies (offshore and onshore wind power, solar thermal power plants) may be able to compete with CCS power plants as early as in 2020.
- If *fossil* fuel prices increase considerably and the CO_2 allowance costs remain low, the generating costs of CCS-based natural gas and hard coal-fired power plants will be higher from 2020 than those of renewable energies. Lignite-fired CCS power plants will follow from 2025 (offshore wind / solar thermal energy) or 2030 (mix of renewable energies).
- Even in the case of *very low* increases in energy prices (but higher CO_2 penalties), the additional costs incurred by CCS would be so high that renewable energies would remain competitive at the same time as in the high price scenario. For lignite, in particular, the high CO_2 penalty would have a negative impact that could not be entirely offset by CO_2 capture.
- If CCS is only made available at a later stage, the increases in costs previously assumed for the year 2020 during the introduction of CCS would be postponed to probably 2025 or 2030. This would mean, however, that renewable energies, depending on these assumptions, would be able to produce energy more cheaply in both the low and high price scenario as early as when CCS is first introduced.

Systems-analytical assessment of CCS in national scenarios

- Should there be a continued significant expansion of renewables and a steady increase in combined heat and power generation in the German power supply, the scope for a further reduction of CO_2 in the remaining fossil segment of power supply using CCS is considerably restricted.
- Ideally, with an established CCS performance of 24 GW, an average of 46 million tonnes of CO_2 could be saved annually up to 2050, compared with an equally sized electricity generation without CCS. This amount constitutes 18 per cent of the total avoidable CO_2 emissions in the electricity sector between 2005 und 2050, and 8 per cent of that within the entire power supply.
- This potential avoidance of 46 million tonnes of CO_2 per year must be set against the annual figure of 64 million tonnes of captured CO_2 (avoidance coefficient of 72 per cent), for which a corresponding (pipeline) infrastructure must be constructed.
- The capacity of fossil fuel-fired power plants will, due to the expected expansion of renewable energies by 2050, steadily decrease to 3,500 hours per annum.
- If the aim remains to significantly expand the share of renewable energies in electricity generation, the opportunity for implementing CCS is significantly reduced if, at the same time, the operating life of nuclear power plants is extended.
- Since much of the power plant mix has already been renewed, it is vital to enable the new fossil fuel-fired power plants constructed to date to be retrofitted as far as possible – even for medium-sized combined heat and power plants – otherwise the achievable segment would be reduced even further.

Conclusive integrative assessment of CCS for fossil fuel-fired power plants and research recommendations

- In view of the current state of technical developments, the political guidelines and the scientific studies published so far, the following six aspects must be highlighted as being essential determining factors for the introduction of CCS. Within the process, it is crucial not to look at CCS from single perspectives, but to integrate it into a holistic analysis of several options for climate protection.
  - The *technology chain* will probably not be *available on a large scale* before sometime between 2025 and 2030. Therefore the use of CCS for power plants could increasingly lose its potential role as a bridging function for renewable energies, as was originally intended.
  - The existing *potential for CCS* will be considerably restricted should there be continued significant expansion of renewables and a steady increase in combined heat and power generation in the German power supply. This effect would be accelerated by the planned lifetime extension of nuclear power plants.
  - The *relative costs of power plants with CCS and electricity generation from renewable energies* are converging: if the dynamics of the expansion of renewables in the electricity sector remain high, it is possible that individual renewable energy tech-

nologies (offshore and onshore wind power, solar thermal power plants) could compete with CCS power plants as early as in 2020.

- The *holistic assessment of environmental impacts* shows that the CCS technology in itself is neither beneficial nor sustainable.
- As research into the stakeholders has revealed, the *social acceptance* of CCS technology depends on, above all, the availability of *long-term stable storage sites*. An effective storage capacity of 5 billion tonnes of CO_2 can be expected to be the lower limit for Germany, as shown by a scenario analysis. As with all other estimates, however, this estimate should be treated with caution.
- Suitable *CCS legislation* is a further essential determining factor for the introduction of CCS, as it defines the speed at which this technology can be realised.

• In view of the obstacles, it is increasingly debatable whether we should focus on CCS as an option in the power plant area, whilst retaining the current priorities in energy policy. Although most of the results of this study relate to Germany, they may, however, also justify similar conclusions for the *rest of Europe*, given EU guidelines to expand renewables and enhance energy efficiency.

• *Globally,* CCS nevertheless remains an important climate protection technology. Coal-consuming countries, such as China and India, which may not have the option of rapidly expanding renewable energies, are increasingly becoming the focus of debate.

• For this reason, research, development and demonstration in the power plant sector remain important, provided they are not at the expense of funding for renewable energies.

• In Germany, discussions now focus increasingly on alternative applications of CCS. Based on the results of this study, it is recommended that the first priorities should be its potential role in industry and biomass rather than in power plants, and there should be an assessment of what this could offer for Germany.

Summary

Chapter 1: Introduction

The RECCS study, presented at the beginning of 2007, was the world's first comprehensive, integrated assessment of CCS technology (WI et al. 2007). By the term "CCS technology" we mean the entire chain, from the separation, condensation and transportation of carbon dioxide to its storage. A unique comparison with the development of renewable energies was also carried out in the study. In the past three years, however, there have been a whole host of new developments at the technical, political and scientific level. To take these developments into account and to include other aspects that, at most, could only be touched on in the RECCS study, we now present this update and expansion of the first study. Due to wide-ranging developments in the power plant sector, the updated study focuses only on electricity generation, and neglects hydrogen generation.

Chapter 2: Global development of CCS between 2007 and 2009

A brief glimpse at the worldwide development of CCS over the past three years shows that the development and demonstration of CCS has been given an increasingly important role in Germany, the European Union (EU) and many other countries (China, the USA and Australia have also been analysed). In Germany, development projects are primarily funded within the scope of the COORETEC (CO2-REduction-TEChnologies) programme of the German Federal Ministry of Economics and Technology and the Geotechnologies Programme of the German Federal Ministry of Education and Research. The construction of two demonstration coal-fired power plants using CCS technology is in the pipeline, and individual power plant units will be equipped with carbon dioxide capture systems. CO_2 scrubbing has already been installed on a trial basis in individual units at two power plant locations and, significantly, the world's first pilot plant for lignite combustion with the oxyfuel process became operational. Throughout Europe, 41 pilot and demonstration projects were set up in the power plant sector, the majority of which were undertaken in England, the Netherlands and Norway, followed by Germany. Additionally, CO_2 capture is being explored in eight known projects within other industrial sectors. Despite, or due to, this wide range of activities, the time when the whole CCS chain will be utilisable on a commercial scale is constantly being postponed, and is now expected to be ready sometime between 2025 and 2030.

CCS and CDM

The integration of CCS in the Clean Development Mechanism (CDM) has also proved to remain highly controversial at an international level. Admitting CCS projects under the umbrella of the CDM was first discussed in 2005 at international climate negotiations. Although a number of consultations have taken place since then between all interested parties and organisations, they have not yet led to any results. The points of contention in the negotiations are not only basic questions on the suitability of CCS as a technology to reduce greenhouse gases, but also complex methodological and legal problems.

Chapter 3: Processes of CO_2 separation in electricity generation

Numerous capture processes are being developed worldwide within the individual technological routes. The majority of the research projects are related to the post-combustion process, for which there are also the most suppliers. In addition to a variety of capture processes, which are based on the absorption, adsorption and membrane methods, recent interest has focused on biological processes (using algae or enzymes). Despite the fact that, from today's perspective, post-combustion technology is the method with the highest efficiency losses, research into it is prioritised with a view to potentially retrofitting power stations. However, potential retrofitting is only appropriate for power stations that have a sufficient length of service life remaining. Although it is said that CCS will not become available before 2020, this primarily involves plants that are currently under construction or in the planning stage. There is no adequate standard definition of such "capture ready" power stations. However, according to a recent survey, 13 of the 16 investors interviewed stated that the coal-fired power plants they had planned or were constructing (only power plants with capacities above 300 MW) were designed to be "capture ready".

Chapter 4: Analysis of the options for the use of CO_2

Possibilities for reusing CO_2 arise in these fields: as a parent substance to produce a variety of materials, ranging from the chemical raw methanol to end products, such as urethane, tensides and urea; or as a technical aid in dry cleaning, fire extinguishers, aerosol cans and cooling devices, along with other applications. Nevertheless, the majority of these processes are brief since the CO_2 is released again very quickly. In the food industry, CO_2 is mainly used as carbon dioxide gas in beverages and to neutralise water. In terms of volume, the possibility of substituting CO_2 used in this industry with captured CO_2 is virtually negligible.

Previous estimates assumed that between much less than 1 per cent and a maximum of 5 per cent of the current quantity of CO_2 produced can be bound to product cycles. In connection with the synthesis of methanol, use of CO_2 as a "raw material" would be significantly different once "cheap, non-fossil hydrogen", for example, or other reducing agents become available, enhancing the potential for reduction. Plastics could then be used on a much larger scale as substitutes for other materials, such as those used in the metal sector (including the manufacture of car bodies).

There are already a number of ideas for using biological processes to capture CO_2 or to absorb CO_2 from the atmosphere. Microalgae are able to absorb CO_2 from flue gases fed to them. The biomass created in the process would have to be separated by centrifugation, for instance, and further utilised (for example, to produce biogas, biodiesel, bioethanol or biohydrogen). Plants of this type would probably be used for smaller CO_2 sources but large areas or volumes are available for such bioreactors. In the area of land plants, work is being undertaken on a genetically modified enzyme development to create a more efficient storage of CO_2 from the air. Microbiological transformation, on the other hand, involves converting carbon dioxide into methane. Other considerations include afforestation and the induction of algal blooms in the ocean.

Other processes and approaches include the carbonisation of biomass, the storage of trees, new catalysis processes to cleave CO_2 in carbon monoxide or to convert it onto a hydrocarbon, the development of new materials and the absorption of CO_2 to minerals.

Chapter 5: Driving forces and attitudes of relevant stakeholders

In recent years, the number of players involved in the public debate on CCS has steadily grown. In 2007, mainly utility companies and environmental organisations were involved in the public debate, and it was given only brief coverage in the media. Today, the issue ignites diverse debate across a whole spectrum of social, economic and political groups.

The topics on CCS technologies now being debated are much more focused. While in 2007 discussions mainly addressed the technical and economic feasibility of the technology, there is now much broader and more open exchange on the topic, involving advanced aspects, such as potential competitive usages with other technologies and liability issues. Reports on CCS are no longer restricted to the context of coal-fired power plant technologies. It is noticeable that greater attention is now being paid to industrial applications of the technology as an option to reduce process emissions. The technology is also being mentioned more frequently in the context of biomass use. In Germany, the focus is primarily on the technical advancement of CCS technologies; most stakeholders believe that these technologies are best implemented and applied in the aspiring industrial nations that have considerable deposits of coal (such as China and India).

The growing expertise about CCS technologies goes hand in hand with stakeholders adopting increasingly strong positions. One specific aspect of this debate, however, remains constant: the opinions and attitudes on the subject of CCS are strongly divided between its opponents and supporters, sometimes even within the same groups (for instance, environmental NGOs and science).

The analysis shows that there is no clear majority among environmental and climate protection organisations either for or against CCS technologies. The relevant industry associations and trade unions, however, are mainly in favour of continuing to explore and implement CCS technologies. A more negative attitude towards CCS is emerging among representatives of church institutions, especially in regions where the use of CCS may directly affect the public and future generations. The majority of parties represented in the Bundestag and the German government support the use of CCS. At federal state level, Schleswig-Holstein federal state government and all parties represented in the Schleswig-Holstein parliament clearly oppose the storage of CO_2. Highly industrialised, coal-producing federal states, such as Brandenburg and North Rhine-Westphalia, on the other hand, are advocates of CCS. A two-level conflict is therefore emerging: at the first level, between federal states with a great CO_2 storage potential and the German government and, at the second level, between the “storage states” and all other federal states.

Advisory committees to the German government mainly have a negative attitude towards CCS technology. These committees highlight the major uncertainties associated with the use of the technology, in particular its storage, and warn against premature strategic decisions being taken. In addition, they believe the technology must not impede the development of renewable energies and the enhancement of energy efficiency. The German Federal Environment Agency, in particular, classifies CCS as unsustainable within the definition of sustainable development. On the other hand, the German Council for Sustainable Development advocates taking a leading role in the development of CCS to facilitate the sustainable use of coal.

As with environmental and climate protection organisations, German research institutions take an ambivalent stance towards CCS technology. Potsdam Institute for Climate Impact Research and Öko-Institut regard CCS as a necessary climate protection option that should be employed in certain sectors (such as heavy industry) or countries (such as China or India) where it is difficult to achieve reductions in CO_2 and the associated structural change. Forschungszentrum Jülich considers CCS to be an important option for Germany, too, whereas this is rejected by the Institute for Futures Studies and Technology Assessment.

Chapter 6: Legal aspects of introducing CCS to power plant technology

Europe

In June 2009, the European Union adopted the CCS Directive (2009/31/EC), which is to be transposed into the national law of all Member States within two years. This Directive, along with other modified legal acts, constitutes a comprehensive regime for the use of CCS technology valid in all EU Member States that is suitable for achieving the pursued objectives. Since the specifications are very detailed in parts, it shows Member States what national CCS policy might look like. At the same time, however, they are given wide scope for implementing and formalising in important areas relating to the policy system.

The controversial and significant topic of liability has been the focus of much discussion. Responsibility for closed storage sites is usually transferred to the state after 20 years if certain requirements are met. Most experts agree that this transfer of responsibility is appropriate. Considering the periods (at least 800 years) required for climate-effective storage and the fact that it is virtually impossible for private enterprises, unlike states, to guarantee their existence for such long periods, this 20-year time limit given in the Directive for transferring responsibility is very short. However, Member States are able to set a longer period for the earliest time possible for transferring responsibility.

With the implementation of the capture ready regulation in the Large Combustion Plant (LCP) Directive, European legislators have accepted a politically negotiated compromise which states that the use of CCS technology (so far at least) is not an actual requirement for the approval of constructing new coal-fired power plants. Whether this will still be the case after the review process, which is expected to take place by 2015, depends on the technical developments and the political decision that may then be required on the obligatory use of CCS technology.

By integrating the entire CCS process chain into the European emission trading scheme, a tool for CCS is activated that can be used to provide incentives to investors from both a safety-related and a business-management perspective. However, important requirements for permanent safe storage and for the investment security necessary for project investors are only described in general and on their merits in the Directive.

Neither does the Directive provide specific guidelines for how authorities should prioritise between different competing projects that require the same geological formation (for instance, geothermal energy or gas storage versus CO_2 storage).

Germany

The applicable German law has been inadequate to the task of legislating for the different procedural steps of the CCS chain. The greatest problems arise in the field of CO_2 injection, solely aimed at permanently removing CO_2. For this reason, projects concerning the permanent storage of CO_2 are only permitted in a few constellations in accordance with the applicable law.

On the basis of this finding and the specifications of the CCS Directive (2009/31/EC), a draft CCS Law intended to encompass the whole CCS process for speedy implementation in Germany was submitted by the German Federal Cabinet in April 2009. In the end, the Bill was not adopted. Overall, the CCS Law was recognisably guided by achieving a transposition close to the specifications of the CCS Directive (2009/31/EC), intending to meet not only environmental and safety requirements, but also the demands governing the necessary investment and legal security for CCS projects. This objective was not fully achieved by the draft CCS Law. The CCS process is not expressly called a transitional technology in the draft of the Carbon Dioxide Storage Act. Although this is not a violation of the guidelines of the CCS Directive, critics in Germany demand a systematical change by declaring the CCS Law as a research law that can be used to enable the exploration of CCS in a limited number of demonstration plants. It is clear that, from today's perspective, the CCS process, and in particular the question of the permanence of CO_2 storages sites, cannot be answered conclusively, and certainly not in general terms.

The provisions for detecting, assessing and resolving conflicts concerning underground usage resulting from the large-scale use of CCS technology were also inadequate. The provisions provide for solutions to individual cases, rather than for extensive, preventive planning. In a renewed attempt at creating legislation, the reservations of the potential federal "*storage states*", underestimated in the "first attempt" at devising a CCS Law explored here, should be taken seriously. The authors are also critical of the regulatory approach because it failed to regulate and specify fundamental legal decisions in a parliamentary act. Instead, they were moved to the level of ordinances. However, the relevant ordinances were not tabled at the same time as the Act. In view of the distinct conflicts emerging between land owners and those with an interest in underground uses, this legal relationship should also be regulated so that the risk of legal uncertainty is mitigated, and all parties are aware of their rights and obligations. If the question of the suitable time to transfer responsibility to the respective federal state is explored in further detail, the general deadline of a minimum of 30 years after the decommissioning of the plant, as stipulated in the draft of the Carbon Dioxide Storage Act, seems appropriate. It is not recommended that new and extended, or shortened clauses, are established in addition to the technology clauses currently used with standards that were formalised over a long period in practice through jurisprudence. This would cause unnecessary legal uncertainty.

Chapter 7: Analysis of the options for storing CO_2

Germany

Underground storage of the greenhouse gas CO_2 is crucial to the whole CCS process chain.The objectives of the analysis were therefore to:

- systematically analyse and compare existing capacity estimates with regard to their methods and assumptions;
- present a cautious, conservative estimate for the effective capacity within the definition of a lower limit for orientation purposes for potential investors and political decision-makers.

This would be not only for Germany, but also for neighbouring countries where CO_2 from Germany could possibly be stored.

Using a scenario analysis, a typical “what-if” examination was conducted in which cautious estimates and assumptions were pooled. Rather than basing the analysis on new geological data, it uses findings given in the literature. It should be pointed out that, due to a lack of practical experience of injecting CO_2, and also a lack of data, both the conservative calculation presented here and existing estimates should be treated with caution.

The “techno-economic resource pyramid for capacity for CO_2 geological storage” is often used to classify the assessed potential. In this concept, a differentiation is made between the total pore space (*theoretical capacity*), the available volume (*effective capacity*, derived from the theoretical capacity by applying an efficiency factor) and the *practical capacity* (which depends, among other things, on source-sink matching, acceptance issues and injection rates).

The present estimates of the CO_2 storage potential for Germany in saline aquifers and depleted natural gas fields (both onshore and offshore) reveal a wide range of *effective capacity* of between 3 and 44 billion tonnes of CO_2. The average can be taken as 17 billion tonnes of CO_2, which was the conservative estimate published in the GeoCapacity project for Germany. The main reason for this extreme range is that the assumptions of storage efficiency vary considerably.

- Efficiency in saline aquifers, which describes the proportion of water in the saturated subsurface that can be displaced by the injected CO_2, ranges from 0.1 to 40 per cent in the analysed studies. Hence the range of fluctuation of capacities is also enormous – for onshore aquifers alone, previous estimates vary between 0.47 billion tonnes (JOULE II), 12 billion tonnes (GeoCapacity), 28 billion tonnes (BGR) and 42 billion tonnes (GESTCO).
- With natural gas fields, efficiency varies between 75 and 100 per cent of the cumulated recovery of natural gas, and leads to a storage potential in the analysed studies of between 1.7 and 2.8 billion tonnes of CO_2.

There is less deviation in the individual studies with regard to the values chosen for the density of CO_2, the proportion of traps and porosity.

For our *own cautious, conservative estimate* the following results can be summarised:

- With the deep saline aquifers, it is assumed that CO_2 can only be injected in trap structures. Many authors justify this limitation because of its higher permanence, leading to greater public acceptance. In addition, every system is viewed as being closed, resulting in an efficiency factor, related to the total onshore aquifer volume, of 0.1 per cent. These assumptions are confirmed by several new studies, which take the lower efficiency factors into account and advocate taking only closed underground systems into consideration. Based on these assumptions, the conservative estimate of the storage capacity for Germany in onshore saline aquifers amounts to 0.84 billion tonnes of CO_2. The sensitivity analyses with efficiency factors 0.045 per cent and 1 per cent yield a range of fluctuation from 0.38 to 8.4 billion tonnes of CO_2.
- The offshore aquifers had already been estimated conservatively in the GeoCapacity report, which is why this calculation is assumed here. It gives an average capacity of 2.9 billion tonnes of CO_2 (fluctuation of 1.88 to 4.4 billion tonnes of CO_2). These values are considerably higher than the capacities for onshore aquifers, even though German onshore aquifers are considerably larger than their offshore counterparts. The reason for this is that, due to a lack of reliable data for offshore aquifers, it was impossible to carry out a comparable cautious estimate, as had been the case for onshore aquifers. If the cautious assumptions for onshore aquifers are moderated and if, as in the upper sensitivity analysis, a higher increase in pressure is permitted, a different relationship between onshore and offshore appears.
- A storage potential in depleted natural gas fields ranging from 1.34 to 1.61 billion tonnes of CO_2 (excluding reserves) and 1.62 to 1.94 billion tonnes of CO_2 (including reserves) was calculated by setting an efficiency factor of between 75 and 90 per cent. This assumption seems to be justified because it is highly unlikely that the pores, previously filled with natural gas, would be completely filled with CO_2.
- Taking all formations together, the cautious, conservative estimate for Germany in this study totals 5 billion tonnes of CO_2 as the basic value. The uncertainty fluctuation yields values from 4 to 15 billion tonnes of CO_2.

If the *total* CO_2 emissions caused by large point sources in Germany (power plants and industry) are considered (388 million tonnes per annum in 2007), then ultimately, 454 million tonnes of CO_2 would have to be captured annually. With the conservative estimate, these emissions can be stored for 12 years (basic value) or for 8 or 33 years (sensitivity values). If the “Realistisch I” scenario is assumed, as calculated in Chapter 10 for Germany, a total of 1.2 billion tonnes of CO_2 could be captured in the power plant sector by the year 2050, which, even under the assumption of the lowest estimate, could be stored within the geographic region of Germany. Only the *effective* capacity, however, was used as the basis in each comparison. The *practical* capacity, generally lower than the effective capacity, would yield lower utilisation periods.

Our analysis of the studies and the adoption of a conservative estimate show that there remain major uncertainties concerning the estimation of storage potential, particularly with regard to saline aquifers. A further outcome is that the variation of individual parameters has a considerable impact on the results of the calculation. We should point out that not only exist-

ing, but also our own estimates, are based on rough data. It is important to state a lower estimate, however, in the sense of a minimum value, to give politicians and industry a basis for planning legislation and further investments.

Since the storage capacities analysed are merely approximate regional estimates, the parameters chosen should be checked and further research and geological investigations should be undertaken to improve accuracy and knowledge. The objective should be to gain extensive geological knowledge of all potential storage sites. This would subsequently establish the availability of potential storage and, therefore, the volume at sites. Although the Catalogue of Storage Capacities in Germany, currently under development, will help to improve the database, it is by no means adequate with regard to the precise assessment of (site-specific) storage options.

In addition, several geo-technical factors could not be taken into account in this study:

- In the discussion about the total quantity of effective storage capacity, it is often presumed that all emissions from point sources can be injected. Instead of the cumulated storage potential discussed here, however, the possible injection rate is likely to be the limiting factor. (Gerling 2010), for instance, estimates the maximum quantity of CO_2 that can be injected annually into storage sites in Germany, based on assumptions by the BGR, to be 50–75 million tonnes of CO_2. Detailed examinations are required here to determine which CCS potentials should, in fact, be implemented on the time line.
- How neighbouring structures are influenced by the injection of CO_2 (for instance, with regard to pressure) and the effect this has on total capacity are only rarely considered in storage calculations. This *interference* should be examined further in practice, and should be included in the calculations to refine this aspect.
- Underground *seismic activity* continues to be important. Areas that are susceptible to natural earthquakes are precluded as storage sites. In addition, seismicity induced by drilling and CO_2 injection should also be analysed and avoided.

Europe

In order to estimate the CO_2 storage potential in Europe, existing publications were assessed and their central assumptions compiled. According to these estimates, capacities in Europe are distributed very unevenly. Depending on the assumptions made in the studies, a total of between 60 and 800 billion tonnes of CO_2 storage potential is available. The potential in neighbouring countries and the North Sea are especially relevant to Germany.

As we were unable to carry out our own cautious estimates for this study, as in the case of Germany, instead we adopted the conservative estimates of the investigated studies. Some of these estimates were supplemented by our own analyses. These estimates yielded an effective storage capacity of 44 billion tonnes of CO_2 for Germany's "neighbouring states": the Netherlands, France, Denmark, the United Kingdom, Norway and Poland. The majority of this capacity is available in Norway, with 21 billion tonnes of CO_2 (48 per cent), followed by the United Kingdom, with 15 billion tonnes of CO_2 (34 per cent). The other countries explored have only small potential at their disposal.

The Utsira formation, with 1 billion tonnes of CO_2, is part of Norway's storage capacity. This conservative estimate assumes an effective capacity with an efficiency factor of 4 per cent and storage only in closed structures.

If the conservative estimate for Germany is added to this figure, the total capacity amounts to 49 billion tonnes of CO_2. Compared with the cumulated emissions of the analysed countries over 40 years (47.6 billion tonnes of CO_2), a virtual balance is achieved. The CO_2 storage potential would therefore have to be virtually exhausted in order to eliminate all CO_2 emissions.

This simplified comparison, however, disregards several difficulties:

- The *increased demand* for energy caused by the capture of CO_2 and the *CO_2 capture rate* have not been included in the estimate. If these are set at 30 and 90 per cent, respectively, the emissions needing to be captured and stored increase by 17 per cent.
- The capacities listed are *effective*, meaning that the necessary geographical matching of sources and sinks would reduce this potential yet further.
- It was assumed in the comparison that the whole quantity of emissions could be stored, which is a highly optimistic assumption if potential injection rates are scrutinised in more depth.
- In addition, the viability and costs of the necessary *pipeline system* should be reviewed (national studies on the costs of CO_2 transport generally only allow for transportation within one's own country).
- Moreover, such an approach would be a *centralistic solution*, since the majority of capacities are located in the North Sea, signalling a significant dependence on just one combined main pipeline route. It can be assumed that economic issues and public acceptance would be the decisive factors when considering a pan-European CO_2 pipeline system.
- Some authors argue that the underground injection of CO_2 is only possible if the same volume of *salt water* is recovered. This generally rules out the storage of CO_2 onshore because the recovered water would also have to be stored or, after being desalinised, would lead to considerable occurrences of salification. The authors, however, believe that the recovery of salt water from deep aquifers beneath the North Sea and the resulting input of CO_2 is a possibility.
- As in Germany, other countries would not be able to capture the whole quantity of current emissions from large point sources for CO_2 storage (for the simple reason that there are legally binding targets for the growth of renewable energies in all EU countries). In order to be able to assess storage capacities realistically, therefore, similar power plant scenarios to those for Germany should be generated for other countries, and a "realistic" quantity of CO_2 matched with the conservative estimates of the storage sites.

This wide range of issues and difficulties described here show that, in all, the storage potential will probably be insufficient for the storage of all emissions. However, it appears the North Sea would have sufficient capacity to at least store some of the northern European emissions.

Enhanced oil recovery (EOR) using CO_2

There appears to be potential for enhanced oil recovery using CO_2 in the North Sea. The obstacles that need to be overcome for a large-scale deployment of CO_2 EOR offshore are the long-term, safe supply of CO_2 and a stable oil price above US$ 100/barrel. The largest capacities will probably be required in the 2020s, by which time it is highly unlikely that a CO_2 pipeline infrastructure will be in existence.

The economic incentive of EOR could promote the introduction of CCS as a climate protection option. If the EOR infrastructure is later used for CCS, the time window in which a platform can be converted must be taken into account. It must also be assessed economically whether it is worthwhile for the company to convert the platform once oil production has finally ended. If the conversion is too expensive, the infrastructure will be abandoned and the storage site may no longer remain usable.

If the life cycle assessment of EOR is considered, it is clear that it cannot contribute to climate protection. On the contrary: for every tonne of CO_2 stored, the production and subsequent use of the oil releases a four-fold amount of CO_2 into the atmosphere. The only advantage would be that by using industry emissions for EOR, the naturally occurring quantities of CO_2 previously used would remain underground and would not be tapped.

Chapter 8: An environmental assessment of CCS compared with renewable energies

In the RECCS study, life cycle assessments were carried out for the first time for the three conventional capture routes. These LCAs were then compared with selected renewable energy plants and other progressive concepts for the use of fossil fuels. The individual processes involved in the capture of CO_2 were modelled in detail for post-combustion plants. For pre-combustion and oxyfuel, however, only the additional energy consumption is included. No new life cycle assessments were generated in this update. However, several new comprehensive life cycle assessments covering all prevalent capture routes applied to lignite-, hard coal- and natural gas-fired power plants have been presented by a number of institutions. Most of these studies were compiled in 2008. The selected studies, however, were restricted to those in which life cycle assessments of the entire CCS chain were created, following the respective ISO standards for life cycle assessments. An analysis was made of the precision with which the individual steps in the process – capture, compression, transport and storage – were modelled and also of what assumptions were made in the process.

The findings of the RECCS study were principally confirmed in the newer studies, and developed significantly. If the entire process chain, including the upstream chains of substances and energies used, is considered, the greenhouse gas emissions from CCS power plants operational in 2020 will only be reduced in total by around 68 to 87 per cent (in exceptional cases up to 95 per cent).

However, other environmental impacts should be considered in addition to greenhouse gas emissions. The higher energy consumption required in all of the processes and the materials used in the capture processes can be perceived in direct proportion to the various impact categories of the life cycle assessment. This factor was only modelled for the post-combustion process in the RECCS study. More recent studies, however, also present findings for pre-combustion (for both lignite and hard coal) and for oxyfuel. Amongst other things, these studies have explored summer smog, eutrophication, soil and water acidification, ma-

rine ecotoxicity and particle emission. Depending on the assumptions made in the studies, the various interactions in the capture processes lead to many trade-offs in the individual environmental impact categories. In some studies, all emissions increase in accordance with the additional energy consumption. Other studies, however, model trade-offs that arise from the simultaneous reduction of other emissions in the course of the CO_2 capture process.

As in the RECCS study, most of the studies conclude that for the post-combustion process increases are observed with virtually all of the environmental impacts (+26 to 250 per cent). The individual processes cannot yet be modelled in detail for pre-combustion and oxyfuel; rough estimates for IGCC show 20 to 66 per cent increases for all environmental impacts and 22 to 80 per cent decreases in all environmental impacts with oxyfuel.

The proportion related to the manufacture of the infrastructure, i.e. the plant required to capture, transport and store the gas, is analysed as being very low (0.3 to 2.6 per cent) in all of the studies. Transportation of the CO_2 is modelled more or less uniformly, even if assumptions regarding the transport distance vary. Leakages of CO_2 in the compression and transportation processes were only partially modelled. Leakages at the CO_2 storage site were neglected by all studies. It is assumed in some studies that the storage site would otherwise not have been approved. Other studies assume that CO_2 would indeed be released, albeit with a long delay, which would be significantly better for the environment than the current high rates of emission. The injection is either not modelled at all, or it is modelled only for the purpose of power requirements or for the required infrastructure.

The largely different assumptions for the CCS chain, the time of use of CCS, the type of reference power plants, the selection of various parameters and the heterogeneous choice of environmental impact categories are particularly conspicuous. As in many other life cycle assessments, this reveals a need for action to harmonise life cycle assessments for CCS technology. Together with the German “Network on Life Cycle Inventory Data”, it is proposed that the aim of harmonising life cycle assessments should be to develop standard guidelines and to then create standard life cycle assessments for CCS reference plants based on these guidelines.

The recommendations of some authors to install a comprehensive monitoring programme for the first CCS power plants should not be restricted just to life cycle assessments. Such a programme would be important for gaining information about the actual emissions caused or reduced due to the capture of CO_2. Such information would considerably improve our understanding of the individual chemical processes, and how they should be modelled.

Even compared to CCS power plants, renewable energies create only a fraction of greenhouse gas emissions. In 2025 (2050), it is estimated that offshore wind will create only 5 to 8 (9 to 15) per cent, solar thermal energy 11 to 18 (13 to 23) per cent and photovoltaics 14 to 24 (7 to 12) per cent of the emissions of CCS power plants. All renewable energies will have improved in absolute terms by 2050, but show higher percentages, with the exception of photovoltaics, because CCS technologies will also improve.

Further aspects are also neglected in life cycle assessment. These include the fundamental, extensive changes to the landscape caused by coal mining, the consequences of a decline in the ground water table, water contamination by water from mines and the creation of enormous slag heaps that have a negative impact on groundwater supply for agriculture and the

surrounding ecosystems. The resettlement or displacement of the population results in the loss of agricultural land and homes. Entire village communities are destroyed, leading to social and cultural problems.

It is not yet apparent whether the transfer of large quantities of carbon dioxide will have a biogeochemical impact on the microbial biota in deep rock formations. Drilling to depths of 3.5 km has revealed bacteria, viruses and fungi. Many of the types of bacteria found in these deep rock formations are completely unknown. Their "function" within this ecosystem has not nearly been researched to a sufficient extent.

Chapter 9: Economic comparison of CCS power plants and renewable energy technologies

After successfully demonstrating the entire CCS chain (the capture, transport and, in particular, storage of CO_2), according to our calculations, electricity generating costs from CCS power plants of between 7.30 and 10.35 ct/kWh$_{el}$ (at power plant) can be achieved by 2020 (assumed real interest rate 6 per cent per annum). The price range depends on both the technology taken into consideration and the price trends of fuel and CO_2 allowances up to 2020. The usage fees for storage sites ("storage fee"), as called for by several federal states and the German Advisory Council on the Environment, have not yet been included.

Two scenarios were considered: very low increasing fuel costs with high CO_2 penalties (scenario C/A) and considerably rising energy costs that cause a surplus of and, therefore, decreasing CO_2 penalties (scenario A/C). In the latter case, considered to be the more realistic scenario, CO_2 avoidance costs in 2020 of € 68/t CO_2 (natural gas), € 43/t CO_2 (hard coal) and € 20/t CO_2 (lignite) are produced.

Depending on further price trends, the long-term cost projections of CCS range from 8.10 to 13.80 ct/kWh$_{el}$ in 2040 and from 8.80 to 15.40 ct/kWh$_{el}$ in 2050. Lignite steam power plants are in the lower region, hard coal power plants (steam and gasification) are in the medium to high range, and natural gas in the top range. Despite increasing running costs, CO_2 avoidance costs decrease due to learning effects by 2040 to € 61/t CO_2 (natural gas), € 36/t CO_2 (hard coal) and €17/t CO_2 (lignite). With the exception of lignite, therefore, they are still a long way from achieving the costs of around € 20/t CO_2 to which the power industry aspires.

The average electricity generating costs of renewable energies are presently around 12 ct/kWh$_{el}$, assuming a representative mix (also calculated at a real interest rate of 6 per cent per annum). When photovoltaics are excluded from the mix, the average costs amount to around 10 ct/kWh$_{el}$. If they continue to be launched at a similar speed as before, average electricity generating costs of approximately 8.8 ct/kWh$_{el}$ (including photovoltaics) and 8.2 ct/kWh$_{el}$ (excluding photovoltaics) can be achieved by 2020. A sustained global increase in market penetration and learning effects give reasons to expect further significant cost degressions for renewable energies over time. By 2050, therefore, the level of costs in the investigated characteristic mix could be around 8.8 ct/kWh$_{el.}$ Technologies such as offshore wind power or geothermal energy could achieve electricity costs of around 5 ct/kWh$_{el}$ if their learning curve continues to be used for the further expansion of global markets.

If the dynamics of the expansion of renewables in the electricity sector remains high, as assumed in the scenario family CCS-EE/KWK (Chapter 10), individual renewable energy technologies (offshore and onshore wind power, solar thermal power plants) will be able to com-

pete with CCS power plants as early as in 2020, which is considered to be the potential starting point for CCS power plants. The average mix is partially competitive even now. If fuel prices increase *considerably*, the generating costs of CCS-based natural gas- and hard coal-fired power plants will be higher from 2020 than for renewable energies. Lignite-fired CCS power plants will follow from 2025 (offshore wind/solar thermal energy) and 2030 (mix of renewable energies). Even in the case of *very small* increases in energy prices, the additional costs incurred by CCS would be so high that renewable energies would remain competitive at the same time as in the high price scenario. The high CO_2 penalty, which cannot be fully compensated by CO_2 capture, has a particularly powerful impact on lignite.

The whole calculation is based on the assumption that CCS technology will be commercially viable by 2020. If CCS is not made available until a later stage, the increases in costs previously assumed for the year 2020 during the introduction of CCS would be postponed to later years (2025 or 2030). This would mean, however, that renewable energies would be able to produce energy more cheaply in both the low and high price scenario as early as when CCS is first introduced On the other hand, renewable energies would then also have more room for manoeuvre if their cost reduction (based on the assumption of learning rates) was also delayed by five to ten years.

Banking analysts confirm the basic assertion of the calculations presented here. In its 2009 industry report on photovoltaics, for instance, the Landesbank Baden-Württemberg also modelled other options of CO_2 reduction using scenarios. Regarding CCS, they conclude that this technology is “not practicable on commercial and economic grounds, not even in Central Europe. Solar electricity generation is not more expensive than CCS (and much cheaper from 2020).” It raises the question: “Which technology should be subsidised in future from taxpayers’ money: ‘cleaning’ conventional, fossil fuel-fired power plants, which have an expiration date, by CCS or supplying industrial society with solar electricity, which is arguably more sustainable.”

According to the assumptions made, therefore, there is no compelling incentive from an economic perspective to favour CCS technologies over the further expansion of renewable energies for power generation. Further considerations show, however, that the issue of generating costs and the break-even point between CCS-based power plants and renewable energies are no longer the only decisive factors from the viewpoint of investors. Our calculation of the electricity costs on an annuity basis is not necessarily the calculation used by investors. The traditional mark-up method in electricity pricing, which enables additional investments, the higher fuel costs and an increasing price for CO_2 permits to be included in our calculation, has now been superseded by the stock market approach. This leads to effects such as the additional CO_2 costs being factored into the price, causing them to be considered as only an item in transit, meaning that they do not influence the calculations of power plant investors. In fact, the current price for electricity is determined by the stock market price, which, in turn, is dependent on the merit order of operational power plants. While research has subsequently proved that renewable energies have led to a decrease in electricity prices, despite their currently higher capital expenditure (since their marginal costs are virtually zero, unlike with expensive natural gas), it remains to be seen how they will influence CCS-based power plants.

Chapter 10: Systems-analytical assessment of CCS in national scenarios

The potential role of CCS in the context of a German climate protection strategy largely depends on previously selected energy strategies. In the occurrence of a continued significant expansion of renewable energies and a steadily increasing share of combined heat and power generation in the German power supply, the scope for a further reduction of CO_2 in the remaining fossil segment of power supply using CCS is considerably restricted. Ideally, with an installed CCS capacity of 24 GW, an average of 46 million tonnes of CO_2 could be saved annually up to 2050, compared with an equally sized electricity generation without CCS. This amount constitutes 18 per cent of the total avoidable CO_2 emissions in the electricity sector between 2005 und 2050, and 8 per cent of that within the entire power supply.

This potential saving of 46 million tonnes of CO_2 per year must be set against the annual figure of 64 million tonnes of CO_2 that would be captured and would require the construction of a corresponding (pipeline) infrastructure. Over 30 years, this scenario would require storage capacities of 1,192 million tonnes if CO_2 capture came to an end in 2050. Alternative scenario mixes considered in sensitivity analyses lead to an annual capture quantity of 44 to 117 million tonnes of CO_2 and cumulated storage capacities of 830 to 2,153 million tonnes of CO_2.

The CO_2 reductions achieved by expanding renewable energies and increasing efficiency in the supply of heat and fuel are considerably larger for the same period. Even if there is a great deal of uncertainty surrounding the costs involved, there is much to suggest that an energy path characterised more strongly by renewable energies would be cheaper in the medium to long term. However, it will necessitate a considerable restructuring of the energy economy and infrastructure. For instance, completely different network structures and energy storage facilities will be required. In any case, CO_2 reductions created by efficiency improvements in the electricity sector can be achieved economically with high returns.

The analysed scenarios are also based on the assumption of a scheduled phasing out of nuclear energy. This leads to the creation of a demand for power plant capacity to fill this gap. This could then be met by renewable energies and carbon capture technologies. However, energy policy-makers are discussing the possible extension of the operational life of nuclear power plants. If this were to happen, the opportunity for implementing CCS is significantly reduced. This would impact upon the objective to realise a considerable expansion in the share of renewable energies in electricity generation. Consequently, there may only be a “suboptimal” contribution left for potential CCS power plants if it is assumed that considerable financial resources will be required for further research, development and demonstration before CCS is commercially available. If, moreover, the earliest opportunity for deployment remains around 2020, it is vital to enable the new fossil fuel-fired power plants to be retrofitted as far as possible – even for medium-sized combined heat and power plants – otherwise the achievable segment would be reduced even further. In addition, a completely different mix of renewable energies would be required, compatible with a respective CCS power plant fleet, that is not suitable for compensating for fluctuating energies.

It follows from the analysis that the existing German energy policy objectives of considerable improvements in efficiency (a doubling of energy productivity by 2020 compared to 1990 levels; a 25 per cent share of combined heat and power generation in 2020) and of the required significant expansion of renewable energies (a 30 to 35 per cent share of renewable ener-

gies in electricity generation by 2020 and an approximately 50 per cent share by 2030) leave only minimal scope for the substantial use of CCS technology, even in the case of ambitious climate protection targets. On the other hand, use of CCS technology would be prudent in a future energy supply that only achieves moderate successes in increasing efficiency and further expanding renewable energies, and which shows only little change compared with the current situation with regard to its structural features.

Chapter 11: Conclusive integrated assessment of CCS for fossil fuel-fired power plants and research recommendations

Objectives

The development and demonstration of CCS for fossil fuel-fired power plants has become increasingly prominent in Germany, the rest of the European Union and many other countries (China, the USA and Australia were analysed).

Particularly at the *international level*, CCS is considered to be vital for meeting global targets for reducing CO_2. In its "Blue Map" scenario of "Energy Technology Perspectives", for example, the International Energy Agency estimates that a 50 per cent reduction in global CO_2 emissions by 2050 (compared to current levels) would require a 48 gigatonne reduction in CO_2 compared to the business-as-usual path (IEA 2008). It has been calculated that CCS can make a 19 per cent contribution to this decrease, with the CO_2 being captured from power stations and industrial sites in roughly equal measures.

The *European Union* also supports the development and take-up of CCS technology. One of the aims, triggered also by deliberations about improving the security of supply, is to be able to use the resource potential of coal without multiplying greenhouse gas emissions.

Although no quantitative targets have yet been set in *Germany*, a variety of development projects have been funded by the German Federal Ministries of Economics and Technology (BMWi) and Education and Research (BMBF). The further development of the climate-friendly generation of electricity from coal is identified as an important task in the Integrated Energy and Climate programme.

Factors determining the introduction of CCS

If we focus on the state of the technical development, policy frameworks and previously published scientific research, six crucial factors determining the introduction of CCS should be highlighted. It is vitally important to consider CCS as part of an over-arching analysis of several climate protection options, rather than from an individual perspective.

1. Large-scale availability of the technology

Numerous uncertainties exist with regard to the applicability of CCS and the resulting (quantitative) role of CCS for climate protection. One of these main uncertainties is the issue of how much time will elapse between the end of testing and actual commercial realisation. Commitment to the timescale for commercial availability of the whole CCS chain (separation, transport and storage) is consistently being deferred in the latest publications and announcements by industry. The years between 2025 and 2030 are now increasingly being referred to as the time by which the technology will be ready for operation.

On the other hand, the agenda for global climate protection must be set in the next ten years. Essentially, this can only succeed using technologies that are established and basically applicable now. These include the whole range of technologies to increase energy efficiency and, primarily, renewables. Even if considerable effort is still required to achieve these targets with regard to establishing a suitable infrastructure (expansion of power networks, power storage), this potential outcome nevertheless leads to conclusions that the use of CCS for power plants (assuming the later availability of the technology) increasingly loses the potential role ascribed to it as a bridging technology. CCS for power stations could primarily play a supplementary role (for example, if the further expansion of renewable energies should stagnate, or the full potential of energy efficiency be exhausted), but the implementation of CCS technology will increasingly focus on other large point sources from the industrial sector, where the fields of application of renewables and other climate protection measures are limited.

2. Available potential for CCS

The potential role of CCS depends not only on the expected timing of its application but also on general developments in the fossil fuel-fired power plant sector. Due to the current power plant regeneration programme, CO_2 capture has arrived too late to be included directly in the planning phase of the majority of fossil fuel-fired power installations in Germany. It is crucial, therefore, that power stations currently under construction can be retrofitted at a later stage.

In the best outcome of our scenario analysis, (scenario “Realistisch I”), an average of 46 million tonnes of CO_2 can be avoided annually up to 2050 with an installed CCS capacity of 24 gigawatts (new construction of 75 per cent of steam and 40 per cent of combined heat and power stations with CCS; retrofitting of 40 per cent of steam and 20 cent of combined heat and power plants), totalling 1.2 billion tonnes by 2050. This amount constitutes 18 per cent of the total avoidable CO_2 emissions in the electricity sector between 2005 and 2050, and 8 per cent of that within the entire power supply system. It is assumed here that, by complying with existing basic political goals, not only the above-mentioned targets to expand the share of renewable energies, but also the doubling of energy productivity by 2020 (compared to 1990 levels) and the share of combined heat and power, rising to 25 per cent, will be detrimental to exploiting the full potential of CCS.

The analysis therefore shows that there is little room for a substantial use of CCS technology (in power plants) in Germany which is reduced considerably further if the commercial implementation of CCS is postponed to 2025 or 2030 or an extension of the operating lives of nuclear power plants is realised.

3. Development of the relative costs of power plants with CCS and renewable energies

The economic assessment of power plants with downstream CCS depends not only on the question of when the additional costs for CO_2 capture are lower than the costs for acquiring CO_2 allowances. It is more about determining relative cost effectiveness. To this end, the timing of competing climate protection options, such as renewables, must also be taken into account.

If fuel prices increase *considerably* and the cost of CO_2 permits remains low, the generating costs of CCS-based natural gas and hard coal-fired power plants will be higher than with

renewable energies from 2020. Lignite-fired CCS power plants will follow from 2025 (offshore wind/solar thermal energy) and 2030 (mix of renewable energies). Even in the case of *very low* increases in energy prices (but higher CO_2 penalties), the additional costs incurred by CCS would be so high that renewable energies would remain competitive at the same time as in the high price scenario. The high CO_2 penalty, which cannot be fully compensated by CO_2 capture, has a particularly significant impact on lignite. If CCS can only be realised later, the increases in costs previously assumed for 2020 during the introduction of CCS would be postponed to later years (2025 or 2030). This would mean, however, that renewable energies would be able to produce energy more cheaply in both the low and high price scenarios as early as from when CCS is first introduced.

4. Holistic assessment of environmental impacts

Only CO_2 emissions created directly at the power plant are generally included in the debate on CCS as a climate protection option. As this analysis shows, when looking holistically at the environmental picture, CCS technology is in itself neither beneficial nor sustainable.

On the one hand, CO_2 capture involves a considerable additional consumption of non-renewable resources, with all of the associated consequences. Due to the additional consumption of primary energy, CO_2 emissions in the power plant process initially rise, so that the actual quantity of CO_2 avoided is considerably lower than the quantity of CO_2 captured. On the other hand, political goals focus on a reduction in emissions of *all greenhouse gases*. Due to the additional consumption of primary energy and the other stages in the process chain, there would be a rise in non-CO_2 emissions, in particular, which cannot be collected by the capture process. It was shown that greenhouse gas emissions from CCS power stations will only be reduced in total by around 68 to 87 per cent, depending on the technology (up to 95 per cent only in exceptional cases of specific combinations of technologies and fuels). Furthermore, some of the other numerous environmental factors increase considerably (and can only be effectively reduced by pure oxygen combustion). This is also due to the additional consumption of energy.

It is the responsibility of politicians to deliberate about whether a reduction in CO_2 emissions can be reconciled with the consequences described here or whether other energy technologies without these disadvantages are preferable. Besides renewable energies, these include existing fossil technologies, such as CHP plants based on natural gas, which already achieve the emission targets set for the future for CCS technologies.

5. Storage site capacity and public acceptance

As our investigations have shown, the availability of long-term, stable storage sites, in particular, will be pivotal in determining the acceptance of CCS technology by the general public. Compared to the first RECCS study, therefore, the range of stakeholders has been extended to political and social stakeholders from the storage regions. The issue of public acceptance has risen far higher up the agenda than was the case three years ago. If CCS technology should prove to be technically viable, commercially available and even competitive, in spite of the presented cost scenarios, the decisive factors are likely to be the question of the availability of suitable storage sites and gaining public acceptance of their use on a large scale.

Scientifically, the question of the availability of potential storage sites for CO_2 emissions from Germany ultimately remains unanswered. The scope of this analysis was, therefore, not re-

stricted to Germany, but was extended to Germany's neighbours where there may be scope for their storing German CO_2 emissions. The objectives were:

- to systematically analyse and compare existing estimates of storage site capacities with regard to their methods and assumptions, and
- to present a conservative estimate, a lower limit, as a benchmark for potential investors and politicians.

The main findings of the analysis are that:

- there are significant uncertainties surrounding the information about storage potentials (this applies explicitly to the conservative calculation, too);
- the specific basic assumptions from the existing studies could not always be applied adequately to this analysis, thereby making it difficult to produce a comparative study;
- according to existing studies, the storage potential within Germany is estimated to be up to 44 billion tonnes;
- taking a cautious, conservative estimate, the available storage capacity must be assumed to be significantly limited (5 billion tonnes of CO_2 was estimated, assuming closed systems and a subsequent efficiency factor of 0.1 per cent for saline aquifers);
- in the event of higher demands, it would be necessary to switch storage to areas in British and Norwegian waters of the North Sea, where there is expected to be sufficient potential;
- even using the conservative estimate, however, the emissions projected in this scenario, which are intended to be realistic, calculate 1.2 billion tonnes of CO_2 up to 2050 for the power plant sector that could need storing, in addition to further industrial emissions;
- EOR (enhanced oil recovery) could act as an inroad for CCS in Europe, if sufficient CO_2 could be made available by 2020. However, this would not be appropriate as an independent climate protection option;
- guidelines for a standardised and documented estimate of storage potentials are required because huge deviations exist in the approach pursued by individual studies, both in their assumption of central parameters and, in particular, in the documentation of these assumptions.

The "storage cadastre", currently being drawn up by the BGR, is expected to constitute a considerable improvement in terms of clarifying data availability, since all existing geological investigations at federal state level will be brought together. Nonetheless, considerable uncertainty will remain until potential storage sites for CO_2 are not investigated individually.

Regardless of the eventual realisable capacity, the question of whether this potential could be exploited quickly enough remains unanswered. It has not yet been explored whether there will be sufficient quantities of CO_2 in a short space of time, as might be expected from a constant flow from large-scale power plants, that can be injected into a storage site. For this reason, it is recommended that there is an investigation of the infrastructure required and the quantities of CO_2 to be transported and injected, using various capacity scenarios for storage sites, coupled with emissions scenarios. The production capacity available to plants for the

capture and injection of CO_2 should also be included in the timeline. Such a study could be developed by using scenarios to show which CCS potential in Germany would realistically have to be available.

6. CCS legislation

A decisive factor affecting the introduction of CCS is the relevant legislation, since it affects the timescale of the implementation. The European "CCS Directive" is considered to be the framework for all activities along the CCS chain. In June 2009, the European Union adopted the CCS Directive, which is to be incorporated into the national law of all Member States within two years. This Directive, along with other modified legislation, constitutes a comprehensive policy for the use of CCS technology valid in all EU Member States that is suitable for achieving the pursued objectives. By integrating the entire CCS process chain into the European emission trading system, a tool for CCS will be activated that can be used to provide incentives to investors from both an investment security and an economic perspective.

Regarding available applicable law in individual countries and the planned transposition of the EU Directive, it can be said that the applicable law is not suitable for capturing the whole CCS process chain, in particular with regard to storage. The prompt creation of a suitable legal framework for CCS is necessary to provide legal and investment security. Given the gaps in the knowledge, a CCS law should provisionally only enable R&D and demonstration projects and then be scheduled for subsequent review. Provisions in anticipation of the need to detect, assess and solve conflicts of interest as a result of a large-scale use of the CCS process should be accommodated.

CCS in the international focus

In view of the limitations presented here, the position of focusing on CCS as an option in the power plant sector while simultaneously retaining the current energy policy priorities (expansion of renewable energies and CHP, exhaustion of efficiency potentials and possibly extending the lifespan of nuclear power plants) is becoming increasingly untenable. Although most of the results from the present study relate to Germany, similar conclusions may well be applicable for the *rest of Europe,* in view of EU guidelines to expand renewable energies and increase energy efficiency.

Nevertheless, *globally,* CCS remains an important climate protection technology: coal-consuming countries such as China and India are increasingly moving centre stage into the debate, and these countries may not have the option of rapidly expanding renewable energies. For this reason, research, development and demonstration in the power plant sector continue to be important activities, as long as they are not at the expense of funding for renewable energies. But the questions set out above are also increasingly coming to the fore, drawing attention to the timeline: what potential does the fossil power plant mix offer in the medium to long term? Which power stations will possess the necessary criteria to make them eligible for retrofitting? Alternatively, should they be rebuilt as CCS power plants if the CCS chain is potentially only available for use from 2030? These questions will be explored in the follow-up project "CCS global", which was launched at the end of 2009 in collaboration with Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.

CCS in industry and in the use of biomass

In Germany, the debate is increasingly being directed towards alternative applications of CCS. Whereas politicians, utility companies and lobby groups still focus mainly on CCS in the power plant sector, research institutes, advisory bodies and NGOs are increasingly emphasising that the capture of CO_2 at industrial point sources and biomass power plants outweigh this in importance. These options for use have only been touched upon in the present study, but should nevertheless be considered briefly here.

- Whereas only greenhouse gas emissions with a target of minus 80 per cent were usually considered in national climate scenarios, in light of higher reductions now being demanded (90 to 95 per cent by 2050), industry will also have to considerably reduce its emissions. Unlike with CCS in the power plant sector, in the industrial context there are virtually no alternative options available that could assist in a further reduction of CO_2 emissions. Industry can only resort to using electricity and heat from renewable energies, where they are used directly (for example, in electricity powered steelworks). In contrast, a significant share of emissions is process-immanent, and cannot be avoided by applying measures such as renewable energies. There is still a definite need for research into the fields of application of CCS in industry across all sectors.
- The application of CCS in biomass plants (power and heat production, fuels) is of interest because “negative” CO_2 emissions can be achieved. By separating the CO_2 absorbed by plants during growth, CO_2 could not only be avoided, but extracted long-term from the atmosphere. This could become relevant if it proves to be impossible to achieve the set reduction targets in other areas. Whereas some studies point to relevant scenarios, there is a need for research into the specific CCS potential that could be implemented in Germany. To this end, it must be taken into account that
- Due to the limited availability of suitable CO_2 storage sites, the potential use of CCS should mainly occur in the industrial sector and for biomass plants. So far, there are no clear, reliable figures for the capacities that could in fact be used in suitable geological formations. If conservative estimates should turn out to be realistic, this space should initially be reserved for these applications. The separation of CO_2 in industry and for biomass plants would have the added advantage that they generally create fewer emissions than large power stations, enabling the gases to be injected into smaller storage sites. With power plants, however, between 100 and 400 megatonnes can be emitted in their lifetime, meaning that emissions from such plants will rarely be deposited at one single storage site.

Based on the results of this study, it is therefore recommended that major attention is given first to the two options of industry and biomass, rather than to power plants, and that their CCS potential for Germany is explored.

1 Introduction

1.1 The need for an update of the first RECCS study

The RECCS study, published at the beginning of 2007, was the world's first comprehensive, integrated assessment of CCS technology in comparison with renewable energies (WI et al. 2007)[1]. As such, the RECCS study has sparked great interest among experts, politicians and NGOs alike.

Over the past three years there has been a multitude of new developments along the entire process chain throughout the world. Germany has played a prominent role by being the location for the first pilot and demonstration power plants either becoming operational (e.g. Schwarze Pumpe by Vattenfall) or entering the planning phase (e.g. RWE's IGCC power plant in Hürth near Cologne). It is also where numerous individual process steps are being tested. Concrete investigations and detailed planning for potential storage sites and a transport infrastructure are currently underway as part of several of these projects.

A wide variety of projects are also at the planning stage in other countries; a flagship programme of demonstration plants is currently being prepared in the EU. Legal frameworks are being devised concurrently. For instance, the CCS Directive came into force in the EU on 25 June 2009 and must now be transposed into national law by the Member States within the statutory period of two years. In parallel with the projects focused on power plants, the exploration and assessment of CO_2 storage sites is also being actively pursued. This link in the CCS chain has so far been regarded as the most insecure element.

The number of scientific publications in the past three years has multiplied in line with the increase in technical developments. The increased interest can also be seen, for instance, from the scale of the International Conference on Greenhouse Gas Control Technologies (GHGT), the ninth of which comprised 900 presentations and 1,400 participants at the end of 2008 in Washington.

In order to take into account the developments of the past three years and to explore further aspects that were lacking in the RECCS study, or that could not be addressed comprehensively, an update and expansion of the first study is presented here. Due to the multitude of developments in the power plant sector, however, we depart from the approach taken in the RECCS study and consider only power generation and not hydrogen generation.

1.2 Content of the present study

Rather than review the entire RECCS study, it was decided to focus on updating the most important areas in which major changes or activities have occurred in the last three years.

1 An English translation was published at the beginning of 2008.

Essentially, these areas are:

- an analysis of the worldwide development of the past three years,
- an update of the stakeholders in Germany and their attitudes,
- an update of the various processes of CO_2 capture in electricity generation currently being tested,
- a compilation of new life cycle assessments for CCS in the power plant sector,
- an update of the cost trend of both renewable energies and CCS power plants in Germany,
- an expansion of the long-term energy scenarios up to 2050 for Germany, including CCS.

Furthermore, three areas have been newly compiled, namely:

- an analysis of the storage potentials for Germany (not only within Germany but also in the northern North Sea), an assessment of previously published information for Germany and Europe in total and the derivation of our own conservative estimate,
- the portrayal of legal aspects with an analysis of the legal developments in Europe, Germany and an outlook for other states within and outside the EU,
- an overview of possible uses of CO_2 in industry.

2 Global development of CCS between 2007 and 2009

Following the RECCS study, an updated overview of German and international developments in the area of CCS over the last three years is given below. Amongst other things, a picture of planned pilot and demonstration plants in Germany and the EU will be presented, together with the current political developments. The report will also give an insight into CCS activities in China, the USA and Australia.

2.1 Political trends and research and development initiatives

2.1.1 Germany

In its Integrated Energy and Climate Programme (IEKP) passed in August 2007, the German government set the objective of reducing national CO_2 emissions by almost 40 per cent between 2007 and 2020 (compared to 1990 levels). Establishing basic conditions for developing and demonstrating CCS is an important prerequisite for implementing the IEKP. The German government has pledged to swiftly devise a legal framework for the capture, transport and storage of CO_2 and to create two or three demonstration projects with an annual storage of "a few hundred thousand tonnes" of CO_2 as quickly as possible (Bundesregierung 2007).

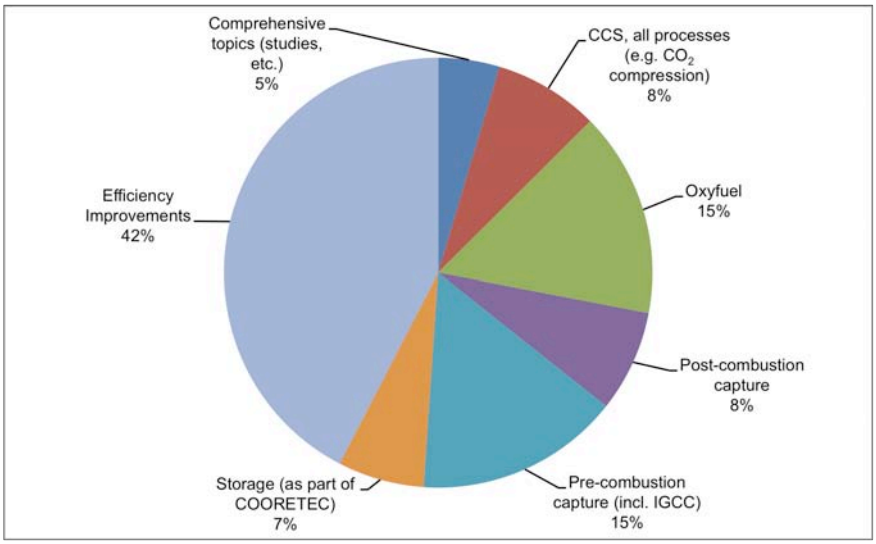

Fig. 2-1 Allocation of the COORETEC budget according to technological sectors (as of 6/2009). Total budget of COORETEC: € 142.5 million

Source: Seier 2009

The significance associated with CCS in German energy and climate policy is backed by the substantial R&D funding for CCS within a number of programmes. The COORETEC programme, under the umbrella of the German Federal Ministry of Economics and Technology (BMWi), brings together German R&D activities in the field of fossil fuel-fired power plant technologies. Within this project, a variety of technologies directly or indirectly relevant to the market launch of CCS are being explored. Such technologies include post- and pre-combustion processes, oxyfuel processes and CO_2 storage technologies (see Fig. 2-1). As of

June 2009, the total budget for the COORETEC project amounted to € 142.5 million (Seier 2009). Of this sum, € 75.5 million is directly connected to CCS. In contrast, the total budget of COORETEC in 2007 was just € 79 million. The significant budget increase is the result of additional funding for CCS from the High-Tech Strategy launched by the German Federal Ministry of Education and Research (BMBF) (BMBF 2007). In addition, economic stimulus programmes recently adopted by the German government also contain funding for research into CCS amounting to € 1.5 billion.

Within the Geotechnologies research programme of the BMBF, twelve new projects have received funding of € 28.6 million since January 2008 under the thematic focus "Technologies for the safe and long-term storage of the greenhouse gas CO_2 II". The projects are listed and briefly described below:

- *ALCATRAP* – optimisation of CO_2 storage by reaction with alkaline residual materials through the ALCATRAP process
- *CLEAN* – CO_2-enhanced gas recovery Altmark
- *CO_2-Leakage* – CO_2-leakage test in a near-surface aquifer for evaluation of monitoring concepts and methods
- *CO_2-MoPa* – modelling and parameterisation of CO_2 storage in deep saliniferous formations for dimension and risk analyses
- *COBOHR* – sealing of wells of CO_2 underground storage for the long-time abandonment before and after the injection
- *CO_2Depth* – software for accurate depth focusing, resolution and localisation of CO_2 storage and migration processes from 3D seismic data
- *CO_2SEALS* – sealing processes in the geological storage of CO_2
- *CO_2SINUS* – CO_2 storage in in-situ converted coal seams
- *COMICOR* – fault-related CO_2 migration, alteration and storage properties in new red sandstone of the Hessian Depression – natural analogue for industrial CO_2 sequestration
- *CORA* – CO_2 reservoir abandonment and post-injection monitoring
- *COSONOStRA* – CO_2-SO_2-NO_x-stimulated rock alteration
- *RECOBIO2* – investigation of the biogeochemical transformation of injected CO_2 in the deep subsurface.

The capture and storage of CO_2 is expected to play a leading role in a new energy research programme launched by the German government. In a paper entitled "*Eckpunkte und Leitlinien zur Weiterentwicklung der Energieforschungspolitik der Bundesregierung"* (Key points and guidelines on the further development of the energy research policy of the German government), published by the Helmholtz Association in September 2009, the development and use of CCS technologies to achieve climate goals are given a high priority in Germany's future energy research policy (Helmholtz-Gemeinschaft 2009).

In Germany, two coal-fired power plants with CCS technology are in the pipeline, and individual power plant units are to be equipped with carbon dioxide capture systems (see also Tab. 2-2 and Section 3.1 for information about the individual processes):

- RWE's planned demonstration power plant with IGCC technology in Hürth should originally have begun operations in 2015. A suitable pipeline route for transporting captured CO_2 and the geological exploration of an applicable storage site in North Frisia and in Eastern Holstein are also in the planning stages. In summer 2009, massive protests were staged at the potential storage site in North Frisia, which caused the state parliament to halt all further exploration of CO_2 storage sites. As a consequence, RWE put a temporary stop to its plans in November 2009 (WDR 2009).
- In Lubmin, near Greifswald, Dong-Energy is planning to equip the new hard coal-fired power plant, which will go into operation in 2012, with post-combustion technology. However, planning permission for the power plant has not yet been given and large numbers of groups have joined forces in the region to protest against the construction of the plant. Shortly before finalising this report, Dong-Energy surprisingly cancelled this power plant project.
- In Brandenburg, Vattenfall plans to test two capture processes in the Jänschwalde power plant near Cottbus: the oxyfuel process, for which a new boiler is being installed, and the post-combustion process, which is being fitted to existing boilers. Construction is due to start in 2011. At the same time, geological investigations are being carried out in two areas (Beeskow and Neutrebbin in Brandenburg) to find a suitable storage formation for captured CO_2 – also for the Schwarze Pumpe pilot plant.
- E.On is planning to build a pilot plant in Wilhelmshaven where a new scrubbing detergent (Econamine-FG+) will be used in the post-combustion process. This pilot plant will be used within the existing power plant units from 2010.

The trial installation of CO_2 capture plants at two power plant units in Germany has already been completed:

- In collaboration with Linde and BASF, RWE launched a pilot plant to scrub CO_2 at the plant site in Niederaußem in August 2009. The CO_2 is separated for test purposes and then released into the atmosphere again.
- In collaboration with Siemens, E.On commissioned a pilot plant at Staudinger power station near Großkrotzenburg in mid-September 2009 to develop an innovative solvent. This project is backed by funds from the COORETEC programme.

Furthermore, Vattenfall put the world's first pilot plant for lignite combustion with the oxyfuel process (pilot plant with 30 MW_{th}) into operation in September 2008 at the Schwarze Pumpe site in the Brandenburg town of Spremberg. The Altmark is also being discussed as a potential storage site.

In Regulation No. 663/2009 of the European Parliament and of the Council of 13 July 2009 on an economic recovery programme (EEPR, see Section 6.1.2.7), the power plant projects run by RWE AG in Hürth and by Vattenfall AG in Jänschwalde were classified as eligible for funding. The contract was awarded only to the project in Jänschwalde, which is one of six projects that will receive € 180 million in funding (IZ Klima 2009b).

The establishment of a legal framework for the capture, transport and storage of CO_2 is dependent on corresponding requirements of the EU Directive on the geological storage of carbon dioxide (see Chapter 6). According to the Directive, the necessary legal and administrative regulations must have been transposed into the law of EU Member States two years after their publication at the latest (that is, by 25 June 2011). Due to the significance of CCS technology to climate protection, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) is responsible for drafting a German CCS law. The process is being accompanied by the BMWi.

A draft for a German "CCS law" was adopted by the German Federal Cabinet on 1 April 2009[2]. The law was discussed during a first reading in the Bundestag on 8 May 2009. During the debate, the German Minister of the Environment stressed the particular importance of CCS to global climate protection, especially with regard to countries with large coal reserves, such as China, India, the USA and Russia. The speaker from the BMWi emphasised the contribution of coal in meeting the world's demand for energy. On the opposing side, there was criticism from representatives of the group of Bündnis 90/Die Grünen, among others. They objected to the fact that the legislative procedure was rushed through and also to the subsidies granted for CCS technology (IZ Klima 2009a). The Advisory Council on the Environment of the German government also voiced its concern (see also Chapter 5).

On 15 May 2009, representatives of the German federal states discussed the Bill in the Bundesrat. In its final advisory opinion, they introduced requests for modification on various technical, ecological and financial issues. There were two central demands made by the Bundesrat. The first was to avoid rivalry in the use of underground storage sites through CO_2 storage by way of a prioritisation of renewable energies (for instance, geothermal energy) and, secondly, a better allocation of the burdens and risks between the German government, the federal states and operators. The federal states, for instance, would like to see the German government assume sole responsibility of the risks involved in the permanent adoption of CO_2 disposal sites (Bundesrat 2009).

On 25 June 2009 – shortly before the law was to be passed in the Bundestag – the Bill was surprisingly defeated due to objections from CDU/CSU representatives (also from Schleswig-Holstein) in whose constituencies explorations for CO_2 storage sites were to be carried out. Reasons given for the rejection included a lack of acceptance of the technology by the public and concerns over powers of intervention in the property of third parties (Märkische Allgemeine Zeitung 2009).

A description of the draft bill is given in Section 6.5, along with an analysis of the remaining questions about its implementation. A detailed description of the various stakeholders in Germany and their assessment of CCS technology are given in Chapter 5.

[2] Draft "*Gesetz zur Regelung von Abscheidung, Transport und dauerhafter Speicherung von Kohlendioxid* (CO2ATSG)" (Law to regulate the capture, transport and permanent storage of carbon dioxide).

2.1.2 European Union

2.1.2.1 The importance of CCS in EU policy

CCS is a central component of the European climate protection strategy. On 17 December 2008, the set of EU directives "Renewable Energy and Climate Change" ("green package") was agreed by the European Parliament. It was ratified in March 2009 by the Council of Ministers and the Commission and was subsequently published, and enacted, on 25 June 2009. The following objectives were laid down in the package:

- to increase energy efficiency by 20 per cent by 2016,
- to lower greenhouse gas emissions by 20 per cent by 2020 (base year 1990),
- to increase the share of renewables in final energy consumption from the current EU average of 8.5 per cent to 20 per cent of final energy consumption in 2020, and
- to raise the share of biofuels in the transport sector to at least 10 per cent.

In order to achieve the planned reductions in greenhouses gases, the EU Commission attaches great significance to CCS technology. In a memo to the European Parliament on the Energy and Climate Package, CCS is said to be "highly important" (European Commission 2008). This is because coal reserves will also have to be used in future to supply energy to Europe and to meet the ever-increasing need for energy in developing and transition countries. In order to utilise the energy potential of coal without multiplying greenhouse gas emissions, the EU is promoting the development and take-up of CCS technology.

The Energy and Climate Package also contains the follow-up to the EU emission trading scheme (ETS)[3] from 2013 and the "CCS Directive"[4]. The latter represents the crucial step for the concrete implementation of power plants with a CO_2 capture system and, in particular, the subsequent storage of CO_2. The Netherlands has made the greatest progress so far in implementing the legal prerequisites for CCS; in Poland, too, arrangements are also being made to transpose the Directive swiftly. These two countries will be analysed in Section 6.4.

The amendment of the ETS Directive ensures the full acceptance of avoided "CCS CO_2" in the European emission trading scheme. CO_2 captured by CCS technology and stored underground is considered to be an emission that has not taken place. At the same time, in accordance with the Directive, emission permits will no longer be allocated from 2013 but auctioned off, creating an incentive to purchase emission permits or to invest in CO_2 capture systems. Moreover, the EU Commission requests Member States to invest at least 20 per cent of proceeds from the trading scheme in R&D and in measures to protect the climate. Within this, CCS is expressly mentioned alongside renewable energy sources (see Section 6.1.2.7 for a more detailed analysis).

Besides the aforementioned Directives and initiatives, the SET Plan ("European Strategic Energy Technology Plan"), passed by the EU Commission in November 2007, is also fun-

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3 Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC (OJ L. 140 of 5 May 2009, p. 63).

4 Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending other legal acts (OJ L. 140 of 5 June 2009, p. 114).

fundamental to the development and distribution of CCS in the EU. CCS is listed as one of six key technologies in this Plan which are to be supported in terms of industrial policy until 2020. With a view to launching CCS into the marketplace, it is intended to establish an EU network of twelve CCS demonstration projects, the construction of which was put out to tender in August 2008. The company Det Norske Veritas AS (DNV) was chosen as the contractor to assist the EU Commission in setting up the network[5].

Fig. 2-2 shows the connections between the different elements of the EU climate package and the SET Plan and the "Action Plan for Energy Efficiency".

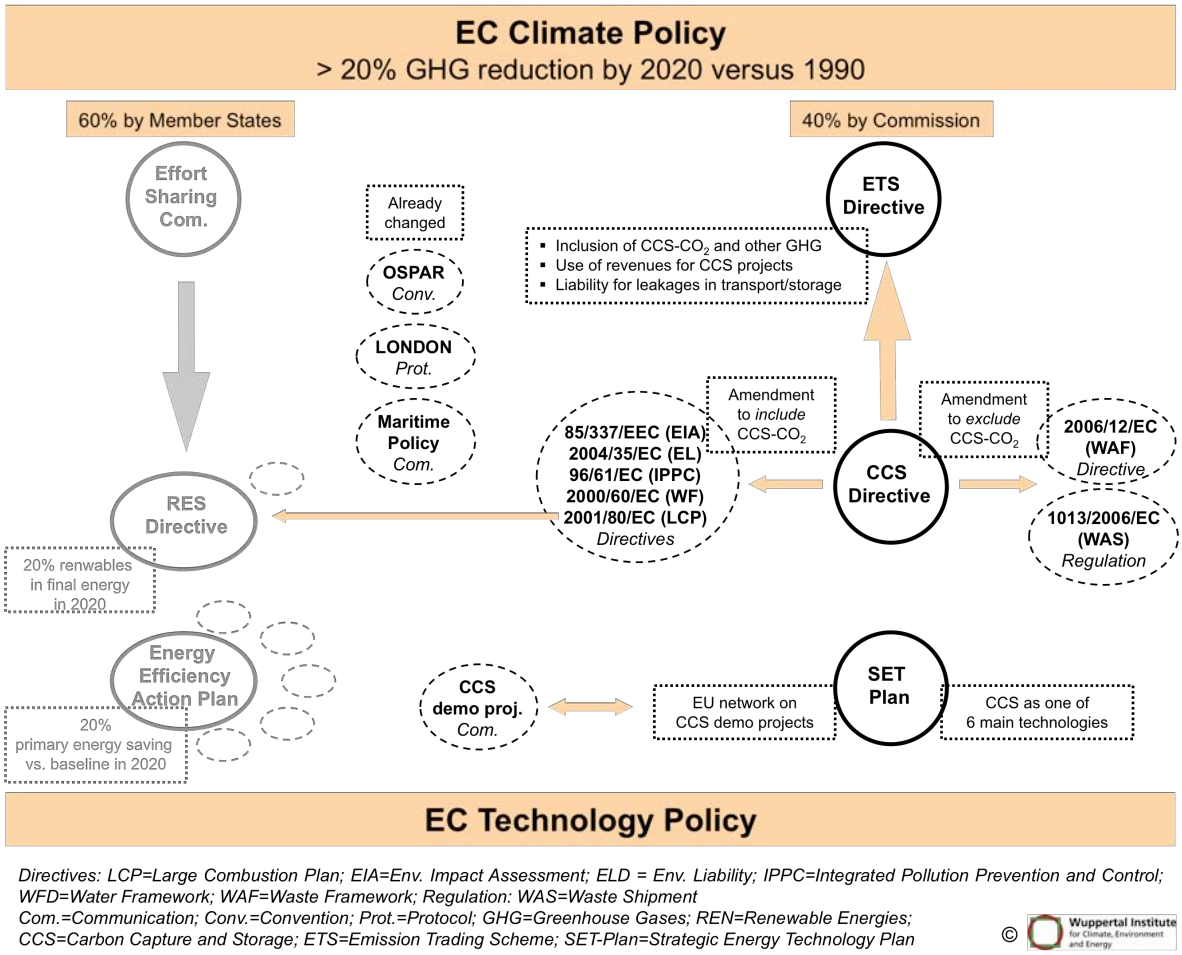


Fig. 2-2 The EU "Directive on the geological storage of carbon dioxide" and its manifold connections to other elements of EU climate policy

Source: Authors' design

The Carbon Capture & Storage Association (CCSA) is a highly active national initiative within the EU. It was established in March 2006 by an industrial consortium to develop CCS technology, primarily in the United Kingdom but also internationally. It aims to be able to demonstrate the large-scale use of CCS in Great Britain by 2014. However, its objective is also to unite business, technology and science sectors in a network so that they can each deliver

[5] For further information: http://ec.europa.eu/energy/coal/sustainable_coal/ccs_en.htm (as of 24 September 2009).

their own expertise to CCS. This would be supported by the UK government and the EU Commission.

The state-level Carbon Sequestration Leadership Forum (CSLF), now consisting of 22 member states and the EU, is also highly committed to the research area of CCS. Twenty projects receive funding from the CSLF, seven of which have already been completed (see Tab. 2-1).

Tab. 2-1 Overview of ongoing and completed research projects funded by the Carbon Sequestration Leadership Forum (CSLF)

CSLF project	Ongoing	Completed
Alberta Enhanced Coal-Bed Methane Recovery Project		X
CANMET Energy Technology Centre (CETC) R&D Oxyfuel Combustion for CO_2 Capture	X	
CASTOR		X
China Coalbed Methane Technology/CO_2 Sequestration Project		X
CO_2 Capture Project (Phase 2)		X
CO_2CRC Otway Project	X	
CO_2 GeoNet	X	
CO_2 Separation from Pressurized Gas Stream	X	
CO_2 SINK	X	
CO_2STORE		X
Dynamis		X
ENCAP	X	
Feasibility Study of Geologic Sequestration of CO_2 in Basalt Formations of (Deccan Trap) in India	X	
Frio Project	X	
Geologic CO_2 Storage Assurance at In Salah, Algeria	X	
IEA GHG Weyburn-Midale CO_2 Monitoring and Storage Project	X	
ITC CO_2 Capture with Chemical Solvents	X	
Regional Carbon Sequestration Partnerships	X	
Regional Opportunities for CO_2 Capture and Storage in China		X
Zama Acid Gas EOR, CO_2 Sequestration, and Monitoring Project	X	

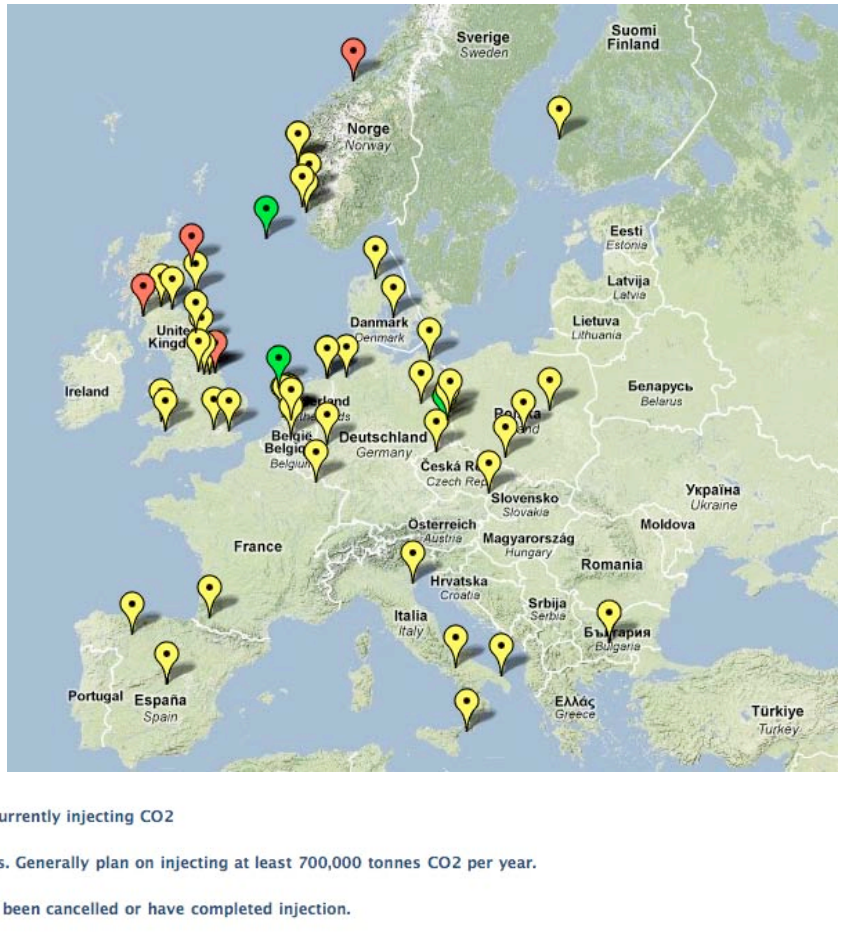
Source: CSLF 2009

2.1.2.2 Pilot and demonstration plants planned throughout Europe

The following Tab. 2-2 shows the currently known CCS demonstration projects in Europe. With regard to quantity, England, the Netherlands and Norway are leading the way, followed by Germany.

Fig. 2-3 also contains CCS projects that have already been dropped – the project in Tjeldbergodden, Norway, that was rejected for financial reasons as well as the project in Peterhead, Scotland, which was abandoned due to a lack of prompt support by the government (van Noorden 2007). In addition, in Australia the IGCC power plant in Perth was abandoned due to the questionable long-term stability of the storage intended for this project. A post-combustion plant in Cooper Basin was also scrapped, for financial reasons. In Canada, the

construction of a new oxyfuel power plant in Saskatchewan was abandoned. Instead, an existing power plant will be equipped with the post-combustion process. Two recently halted European projects – a project in Aalborg (Denmark) was abandoned due to protests by the public and a project in Mongstadt (Norway) was also stopped for financial reasons – have not yet been entered on the map (Wolff 2009).



Sites which are currently injecting CO2

Planned CCS sites. Generally plan on injecting at least 700,000 tonnes CO2 per year.

Sites which have been cancelled or have completed injection.

Fig. 2-3 Overview of ongoing, planned and abandoned or completed CCS projects in Europe

Source: Scottish Centre for Carbon Storage, School of GeoSciences, University of Edinburgh (www.geos.ed.ac.uk/ccsmap)

Tab. 2-2 List of known European CCS pilot and demonstration projects from the power plant sector (as of 9/2009)

Country/Location	Capture technology	Industry	Power output	CO_2 captured	Storage	Players	Commencement
			MW_{el}	Mt/a			
Bulgaria							
Maritsa	Pre-combustion	Electricity	650	3.43	Depleted oil and gas fields	Bulgarian Energy Holding	not specified
Denmark							
Kalundborg	Post-combustion	Electricity	600	3.58	Saline aquifer	Dong Energy	2015
Aalborg	Post-combustion	Electricity	470/ (310 following retro-fit)	1.8	Saline aquifer	Vattenfall	2013, halted due to protest
Finland							
Meri Pori	Oxyfuel or post-combustion	Electricity	560 (400-450 fol-lowing retrofit)	3.35	not specified	Fortum, TVO	2015
France							
Lacq plant + Rousse Feld	Oxyfuel	Electricity	30		Depleted oil and gas fields	Total, Alstom, Air Liquide	2010
Germany							
Jänschwalde	Oxyfuel and post-combustion	Electricity	250 (oxyfuel) <250 (post-comb.)	1.79	EGR or saline aquifer	Vattenfall	2015
Wilhelmshaven	Post-combustion	Electricity	500 (100 captured)	0.6	Saline aquifer	E.on	2015
Hürth	Pre-combustion	Electricity	450	2.8	Saline aquifer	RWE	2015
Großkrotzenburg Staudinger	Post-combustion	Electricity	510 (net)	not specified	not specified	E.on	2009

Country/Location	Capture technology	Industry	Power output	CO_2 captured	Storage	Players	Commencement
			MW_{el}	Mt/a			
England							
Kingsnorth	Post-combustion	Electricity	800	2	Depleted oil and gas fields	E.on UK	2014
Ferrybridge	Post-combustion	Electricity	500	not specified	Saline aquifer	S&S Energy	2015+
Tilburry	Post-combustion	Electricity	1600	9.56	Depleted oil and gas fields	RWE nPower	2016
Humberside Killingholme	Pre-combustion	Electricity	350	2.5	Depleted oil and gas fields	E.on UK	2016+
Hatfield	Pre-combustion	Electricity	900	4.75	Depleted oil and gas fields	Powerful Power Ltd.	2012-2014
Teesside	Pre-combustion	Electricity	800	4.22	Depleted oil and gas fields	Centrica, Progressive Energy, Coastal Energy	2013
Onllwyn	Pre-combustion	Electricity	450	2.4	not specified	Progressive Energy, BGS, CO_2Store	not specified
Longannet	Post-combustion	Electricity	3390	not specified	Saline aquifer	Shell/National Grid	2012
Italy							
not specified	Post-combustion	Electricity	242 (net)	1.5	Saline aquifer	ENEL	2014
not specified	not specified	Electricity	320 (net)	2.1	Saline aquifer	ENEI	2016
Saline Joniche RC	Post-combustion	Electricity	1320	3.94	not specified	SEI (Rätia Energie & Partners)	not specified

Country/Location	Capture technology	Industry	Power output	CO_2 captured	Storage	Players	Commencement
			MW_{el}	Mt/a			
Netherlands							
Eemshaven	Post-combustion	Electricity	40	0.2	Depleted oil and gas fields	RWE Power, BASF, Linde	2015
Maasvlakte Rotterdam	Post-combustion	Electricity	1070 (100 captured)	5.6	Depleted oil and gas fields	E.on Benelux	not specified
Pistoolhaven Rotterdam	Post-combustion	Electricity	845	not specified	not specified	ENECO, International Power	2011
Eemshaven	Pre-combustion	Electricity	1200	4.14	Depleted oil and gas fields	Nuon	2013
Europoort Rotterdam	Pre-combustion	Electricity	450	2.5	Depleted oil and gas fields	CGEN NV	2014
Rotterdam	Pre-combustion	Electricity	1000	4	Depleted oil and gas fields	Essent	2016
Norway							
Bergen	Post-combustion	Electricity/refineries	280 MW_{el} 350 MW_{th}	1.5	Saline aquifer	Statoil Hydro, Gasnova	2014
Hammerfest	Post-combustion	Electricity	100	not specified	Saline aquifer	Hammerfest Energi, Sargas, Siemens	not specified
Husnes	Post-combustion	Electricity/other	400	2.5	Saline aquifer	Tinfos, Sor-Norge, Eranet, Sargas	not specified
Karsto	Post-comb./ oil + gas	Oil and gas	420	1.2	Saline aquifer	Aker, Fluor, Mitsubishi	2012
Mongstad	Post- or pre-comb.	Electricity	450	1.2	Saline aquifer	BKK	2014, abandoned for financial reasons

Country/Location	Capture technology	Industry	Power output	CO_2 captured	Storage	Players	Commencement
			MW_{el}	Mt/a			
Haugesund	not specified		400-800	not specified	not specified	Haugaland Kraft	2015
Poland							
Warsaw	Post-comb./electricity	Electricity	480	2.87	not specified	Vattenfall	2015+
Kedzierzyn Kozlelaskie	Pre-combustion	Electricity/chemical industry	500 MW_{th} Syngas+ 250 MW_{el}	3.4	Saline aquifer	PKE/ZAK	2014
Belchatow	Post-combustion	Electricity	858 (1/3 CCS)	5.1	Saline aquifer	PGE, ICPC, CMI, PGI	2013
Scotland							
Cockenzie	Post-combustion	Electricity	not specified	not specified	Saline aquifer	Scottish Power	not specified
Spain							
Compostilla Leon	Oxyfuel	not specified	500 (400 CCS)	not specified	Saline aquifer	Endesa	2015
not specified	Post-combustion	Electricity	800 (200 CCS)	not specified	Saline aquifer	Union Fenesa	2016-2017
Czech Republic							
Hodonin SE	Post-combustion	Electricity	105	0.5	Saline aquifer	SE.Power	2015
Ledvice N	Post-combustion	Electricity	660	3.48	Saline aquifer	N.Power	2015

Source: modified from ZEP 2008, authors' additions

Some of the programmes and projects presented in the RECCS Report have since been completed. A brief overview (selection) of the results is given below:

- *CATO*: The first phase of this Dutch research programme has been completed. CO_2 sources and sinks were quantified, the costs of capturing and transporting CO_2 were determined and the necessary infrastructure and its optimum pipeline routes were planned. In addition, a number of capture processes were tested in pilot plants, of which the SEWGS process (Sorption Enhanced Water Gas Shift) proved to be very promising. The SEWGS process can be implemented in both natural gas and coal-fired power plants, and has lower efficiency losses than other processes. Furthermore, it is less expensive than conventional scrubbing processes (see also Section 3.1). The follow-up programme CATO-2 focuses on the demonstration and integration of the CCS technology chain in the existing power plant fleet. In addition, strategic information for political and investment-related decisions is to be compiled and made available.
- *GeoCapacity*: This project was an expansion and update of the GESTCO project, in which the geological storage capacities of a number of selected European countries were investigated. One of the tasks completed in the GeoCapacity project was to provide a first conservative estimate of the storage capacity in saline aquifers in the German North Sea (see Section 7.5.3).
- *Geotechnologies*: The first 3-year phase of this R&D programme initiated by the BMBF was completed in mid 2008. Using the knowledge gained from this first phase and the questions it raised, the second phase was designed as a further development of the first phase (see also Section 2.1.1).

2.1.3 A glance at developments outside the EU

Activities are taking place throughout the world, but especially in the USA, Australia, China and Japan (see Fig. 2-4). Algeria and the United Arab Emirates are also active in the field of CCS. In the following sections, developments in the USA, Australia and China will be analysed in further detail.

2.1.3.1.1 China

General development

Due to China's strong economic growth, there has been a vast expansion of coal-fired power plants there. Since China has large coal reserves, which it intends to use because of the country's rapidly increasing demand for energy, many experts regard the use of CCS technology here as crucial in supporting global endeavours to reduce emissions.

Although the development and commercialisation of CCS is not yet China's top political priority, the number of international and national research, development and demonstration projects in China is increasing, especially due to the growing global awareness and concern about climate issues. On 14 June 2007, the Chinese government published a paper entitled *"China's Scientific & Technological Actions on Climate Change".* In it, it resolves to establish a roadmap for the development and demonstration of CCS and to complete capacity-building activities as well as research, development and demonstration projects (MOST et al. 2007). Furthermore, CCS is one of the key topics in the area of "Clean Coal Technology" within the

863 programme of the 11th Five-Year Plan (2006-2010). The 863 programme was initiated in 1986 (86) in the month of March (3) with the aim of advancing the development of key technologies of fundamental importance to national economic development and security. Around RMB 20 million (€ 2.2 million)[6] are being made available within the 863 programme from 2008 to 2010 to carry out R&D into CCS. The research focuses on CCS in combination with IGCC power plants, since this option leads to lower efficiency losses than capturing CO_2 from the flue gas of conventional coal-fired power plants (Morse et al. 2009).

Fig. 2-4 Overview of ongoing, planned and abandoned or completed CCS projects in the USA, Australia, China and Japan

Source: Scottish Centre for Carbon Storage, School of GeoSciences, University of Edinburgh (www.geos.ed.ac.uk/ccsmap)

Numerous R&D projects on the subject of CCS are currently being planned and completed in China. Here, a distinction can be made between Chinese initiatives and international co-operative projects.

Chinese CCS projects

PetroChina has invested around RMB 200 million (€ 21.6 million) to perform enhanced oil recovery at ten oil production stations in the Jilin oil field. In December 2005, China Huaneng Group and seven other Chinese energy suppliers joined forces to establish the GreenGen Corporation to develop, demonstrate and distribute CCS technology. GreenGen plans to start capturing CO_2 at a pilot plant in 2009. The process is to be tested on a 100 MW plant in 2014. These two steps are intended as preparation for constructing an IGCC power plant with CCS in 2017. The plant, to be built at the Tianjin site, will be designed for a capacity of 400 MW (Shisen 2007). It will later be extended to 650 MW. Since the power plant will be built close to several chemical plants, the resulting synthesis gases, waste heat, electricity and other by-products such as hydrogen will be exploitable. It is intended to use the captured CO_2 to enhance oil recovery (EOR).

6 This and the following conversions are based on the average exchange rate of RMB (renminbi) to € in the period from 1 January to 4 September 2009 (RMB 0.10821 = € 1).

Other plans are being advanced by Shenhua Group, which recently completed a large-scale coal hydrogenation plant in Erdos, Inner Mongolia. According to Shenhua, the plant, which is intended to produce diesel, naphtha and liquefied petroleum gas (LPG), was recently put into operation (China Daily 2009). The hydrogen required for the hydrogenation process is reportedly produced using coal gasification. Shenhua is considering capturing the CO_2 produced during gasification and injecting it into a nearby oil field to enhance oil recovery. It is reported that around 3.6 million tonnes of CO_2 will be captured annually (Morse et al. 2009).

International cooperative projects in the area of CCS focusing on China

In addition to the activities of Chinese players, use of CCS in China is being promoted by bilateral or multilateral cooperative projects. The EU, Japan, the USA and Australia are particularly active in this area. Their current activities are briefly described below.

- *European Union:* Under the leadership of Great Britain, the EU, in collaboration with the Chinese government, is implementing the *"Near-Zero Emissions Coal Technologies" (NZEC)* project, which was initiated in 2005 at the 8th EU-China summit in Beijing. The project comprises three work phases (Haydock 2008):
  - *Phase 1 (up to the end of 2009):* Completion of capacity-building measures for the assessment of potential CO_2 storage sites in China and of case studies for the selection of suitable technologies for CO_2 capture; identification of potential CO_2 storage sites in China, creation of a technological and political roadmap for the development and distribution of CCS in China. The results of Phase 1 were presented at a workshop in China in autumn 2009.
  - *Phase 2 (2010/2011):* Detailed design of a CCS demonstration project.
  - *Phase 3 (up to 2014):* Construction and operation of the CCS demonstration power plant.

  In addition to NZEC, the EU is also involved in the project *"COoperation Action within CCS CHina-EU" (COACH)*. The aim of the project is to lay the foundation for the development of large-scale coal-fired power plants with CCS, and to strengthen cooperation between the EU and China in this area. Various aspects of the technology are being explored in the project. These include the assessment of various capture processes with regard to technical, environmental and economic factors, the derivation of criteria for the selection of potential plant sites and the identification of suitable financing mechanisms. The results of the project are to be integrated in a roadmap for the large-scale use of CCS in Chinese coal-fired power plants.

  The *"Support to Regulatory Activities for Carbon Capture and Storage" (STRACO$_2$)* project focuses on the legal and political issues surrounding CO_2 storage. It is part of the 7th European Framework Programme, and aims to promote the development and implementation of a regulatory framework for the distribution of CCS in the EU and China.

- *Japan:* In May 2008, Japan and China signed an agreement to carry out a project to capture 1–3 million tonnes of CO_2 annually at the Harbin power plant in Heilongjiang Province. The CO_2 is transported along a 100 km pipeline to Daqing oil field and injected into the oil field for EOR.

- *USA:* In 2004, the USA and China formed a bilateral working group on the subject of climate change, which identified CCS as one of ten core topics for joint R&D projects. In the meantime, the USA is financing a number of CCS projects in China. One of these projects is *"Building Regulatory Capacity in China – Guidelines for Safe and Effective Carbon Capture and Storage".* In this project, the World Resources Institute and Tsinghua University are drawing up guidelines and best-practice examples for the implementation of CCS, and are offering capacity-building measures for policy-makers. The guidelines address all stages of the CCS process. Special emphasis is placed on guaranteeing the permanence of storage sites.

  The new U.S. administration has instigated further initiatives for cooperation in the area of CCS. In July 2009, representatives of the U.S. and Chinese governments signed a *"Memorandum of Understanding to Enhance Cooperation on Climate Change, Energy and Environment".* In particular, the memorandum aims to enhance cooperation within the framework of capacity-building measures, R&D projects and initiatives to spread climate-friendly technologies. A total of ten core topics are mentioned, one of which is CCS technologies. Joint R&D projects are expected to be coordinated by the US-China Clean Energy Research Center. The foundation of this centre was announced by the U.S. Department of Energy in July 2009. CCS is one of the top-priority subjects. The centre, which will be based in both China and the USA, is equipped with a total budget of US$ 15 million (€ 11 million)[7] (DOE 2009a).

- *Australia*: In 2007, the *"Australia-China Joint Coordination Group on Clean Coal Technology"* (JCG) was founded to foster the development, application and transfer of coal technologies with low greenhouse gas emissions. JCG's budget in 2008/2009 amounted to US$ 20 million (€ 14.8 million) (Australian Coal Association 2009). The JCG is based on previous bilateral and multilateral initiatives such as the *"Asia-Pacific Partnership on Clean Development and Climate Change"*. Among others, the "China Australia Geological Storage" (CAGS) project, which conducted a detailed assessment of potential CO_2 storage sites, was produced within the partnership under the leadership of Geoscience Australia and the Chinese Ministry of Science and Technology.

2.1.3.2 USA

Within the sub-area of coal technologies, CCS is one of the top priorities of U.S. technology policy. The most important ongoing R&D projects in this field are the "FutureGen" and "Carbon Sequestration" projects. Other projects, such as the "Advanced Turbines" project, which develops turbines for low-carbon IGCC power plants, have synergies with CCS projects. Fig. 2-5 shows that "FutureGen" and "Carbon Sequestration" received the highest allocation of funding in the area of coal in 2008. With a total budget of almost US$ 500 million (€ 369 million), these two projects represented a share of around 40 per cent. In 2009, the R&D budget for coal technologies was increased substantially by the *"American Recovery and Reinvestment Act of 2009 (Recovery Act)"* to overcome the financial crisis. The U.S. government

7 This and the following conversions are based on the average exchange rate of USD to € in the period from 1 January to 4 September 2009 (€ 0.73828 = $ 1).

made over US$ 1.3 billion (€ 959.8 million) available for large-scale CCS projects (Burks et al. 2009).

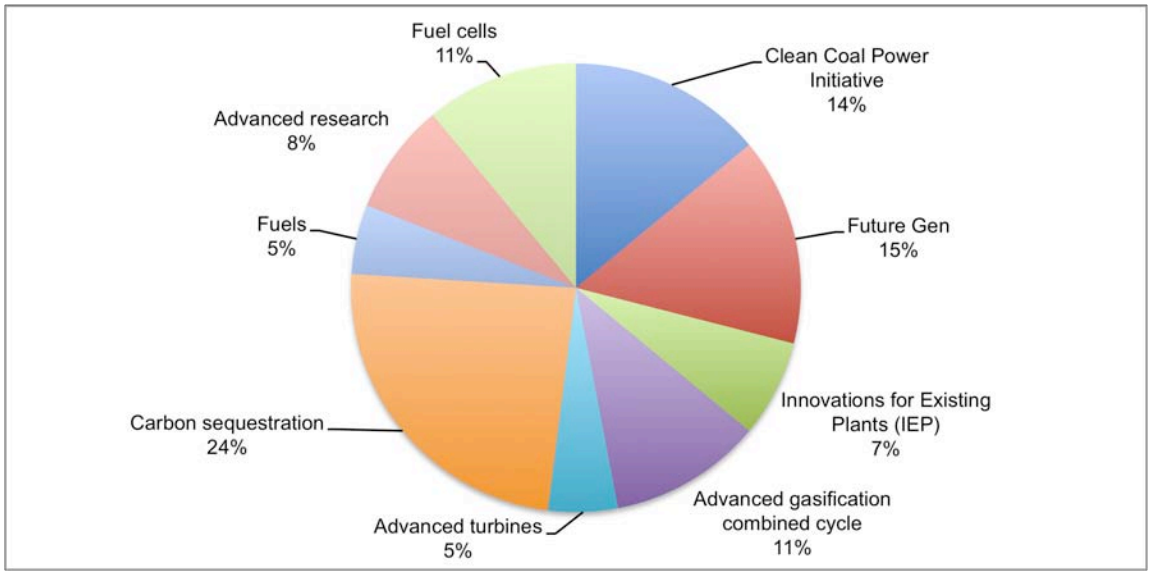


Fig. 2-5 U.S. R&D budget in the area of coal technologies (as of 2008). Total budget: approximately US$ 500 million (€ 369 million)

Source: DOE 2008; Slutz 2008

The FutureGen project in particular is expected to benefit from the additional funding. FutureGen aims to build a 275 MW polygeneration plant in Mattoon, Illinois, that will produce electricity and hydrogen through coal gasification. The project is being led by an international consortium, in which the U.S. Department of Energy acted as the financier until recently. Since 2008, however, the project and the role played by the ministry as financier were questioned, due to substantial increases in costs caused by internationally rising investment expenditure for large-scale plants. In July 2009, the FutureGen consortium and the U.S. Ministry of Energy finally signed an agreement laying down further steps for the project. By the beginning of 2010, the consortium aimed to present a provisional design of the plant, specify its project cost estimates, put forward a financing scheme, secure further investors and, if necessary, carry out additional tests on the subsurface. The ministry and the consortium will decide on the continuation of the FutureGen project, based on the results of this work. Both parties consider a continuation as the preferred solution. The financial contribution of the U.S. government is expected to be significantly higher than in 2008, at US$ 1.073 billion (€ 738.4 million). Over 90 per cent of the funding is expected to come from the "Recovery Act". Thus state funding for FutureGen alone would be around double the entire R&D budget for coal technologies in 2008. The FutureGen consortium is expected to make a financial contribution of US$ 1 billion (DOE 2009b).

The above-mentioned "Carbon Sequestration" project covers all phases of the CCS process, and is subdivided into three parts:

- *"Core Research & Development":* Comprising technical R&D activities in the areas of capture, storage and monitoring the CO_2 storage sites, simulation and risk assessment of CO_2 storage, as well as possibilities for CO_2 exploitation. In August 2009, the U.S. Ministry of Energy announced it would fund 19 projects to determine, assess and simu-

late the risks involved in underground CO_2 storage. The ministry is making a total of US$ 27.6 million (€ 20.4 million) available for this purpose (DOE 2009c).

- *"Infrastructure":* Includes "Regional Carbon Sequestration Partnerships" and other large-scale CCS projects. The partnerships, realised in cooperation with industrial players, are to help the identification and development of suitable technologies, necessary infrastructure measures and regulations for CCS projects in certain regions. Differing geographic framework conditions for CO_2 storage in the USA necessitate a regionally differentiated approach. At present, there are seven regional partnerships involving 43 U.S. federal states and over 350 authorities, universities and enterprises (NETL 2009).
- *"International Cooperations":* In this area, international cooperations and networks are funded to further CCS, e.g. the Carbon Sequestration Leadership Forum (CSLF), financed by the Ministry of Energy, the Asian-Pacific Partnership and support for other international demonstration projects.

In addition to R&D projects, the U.S. government is endeavouring to develop a legal framework for CO_2 storage in geological storage sites. In the process, considerations are given to integrate the special demands of CO_2 storage in the existing regulation regime, e.g. in the *"Underground Injection Control Program"* (UIC). Moreover, numerous other legislative initiatives to regulate CO_2 storage have also taken place recently (for further details, see Section 6.3.1).

2.1.3.2.1 Australia

The CCS strategy of the Australian government comprises three elements:

- *Technical research and development:* The government supports CCS-relevant research projects carried out by the "Commonwealth Scientific and Industrial Research Organisation" (CSRIO) and by "Geoscience Australia". It also finances two research institutions that focus particularly on CCS, namely: the "Cooperative Research Centre for Greenhouse Gas Technologies" (CO_2CRC) and the "Cooperative Research Centre for Coal in Sustainable Development" (CCSD). Sixteen CCS projects are currently being planned or completed in Australia. Of these, eleven projects deal with CO_2 capture and five with CO_2 storage. Fig. 2-6 shows the geographical distribution and status of the projects. The "CO_2CRC Otway Project" is the Australian government's most advanced R&D initiative. Since April 2008, 150 tonnes of CO_2 per day have been pumped into a depleted gas field at a depth of up to 2 km. A total of 50,000 to 100,000 tonnes of CO_2 are to be injected within the space of two years. The project, which comprises a comprehensive programme for monitoring the storage sites, is worth some $A 40 million (€ 21.8 million)[8]. It is being realised by a consortium made up of 15 enterprises and seven government agencies (CO_2CRC 2009).

8 This and the following conversions are based on the average exchange rate of $A to € in the period from 1 January to 4 September 2009 (€ 0.54559 = A$ 1).

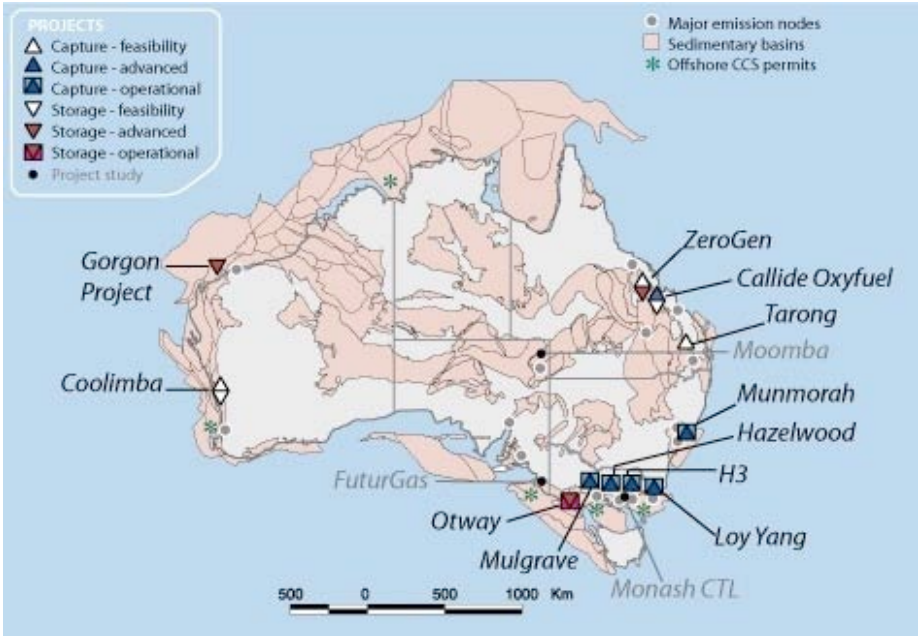


Fig. 2-6 Planned and existing CCS projects in Australia

Source: CO_2CRC 2009

- *Development of a legal framework and of monitoring standards:* The government intends to develop a legal framework for CO_2 capture and storage, as well as standards for monitoring storage sites in cooperation with industrial enterprises and regional governments (for further details, see Section 6.3.2).
- *Enhancement of and participation in international CCS activities:* In the third element of its CCS strategy, the Australian government supports international initiatives to spread CCS technology. Such initiatives include the "Asia-Pacific Partnership on Clean Development and Climate" and the CSLF. Furthermore, the Australian government advocates the stronger integration of technology in the UN Framework Convention on Climate Change, and is in favour of its inclusion in the Clean Development Mechanism (CDM).

2.1.4 International negotiations on considering CCS under the Clean Development Mechanism (CDM)

In recent years, the integration of CCS in the Clean Development Mechanism (CDM) has evolved into a highly contentious issue in international climate negotiations. The CDM enables industrialised countries to fulfil some of their obligations to reduce greenhouse gases in developing countries. The projects aim to make a contribution to sustainable development in developing countries, and must be carried out in addition to reduction measures already taken.

Compared with emissions in the project case, the reduction of emissions is determined using a reference scenario (also called a baseline). According to a specified procedure to validate and certify the reduction of emissions, corresponding emission permits – called "Certified Emission Reductions" (CER) in the case of CDM – are generated. A prerequisite for validation is a methodology for determining the reference scenario that has been approved by the Executive Board (EB) of the CDM.

Approval of CCS projects under the umbrella of the CDM was initially discussed in 2005 within the international climate negotiations, since three proposals for calculating reference scenarios and monitoring CCS projects had previously been submitted to the EB of the CDM. However, none of the submitted methodologies were approved because they failed to provide sufficient precision on methodological and accounting issues involving CCS projects.

At the Conference of the Parties (COP) and the 1st Conference of the Parties of the Kyoto Protocol (MOP) in Montreal in December 2005, the Parties to the Kyoto Protocol were requested to produce statements on the subject. In the ensuing years, further consultations were held with all interested parties and organisations on the topic of CCS-CDM. At the COP/MOP 2 in Nairobi at the end of 2006, the EU, Canada, China, Japan, South Africa and in particular the OPEC countries voted in favour of considering CCS under the CDM. The groups of the Least Developed Countries (LDCs), the Alliance of Small Island States (AOSIS) and Argentina, Brazil and Venezuela positioned themselves against such measures. The Parties agreed on a two-year negotiation process under the umbrella of the Subsidiary Body for Scientific and Technology Advice (SBSTA), in order to be able to make a decision at the COP/MOP 4 (Watanabe et al. 2007).

However, the agreed negotiation process did not lead to any conclusive result. At the Climate Conference in Poznań in December 2008, two proposals – one that supported considering CCS under the CDM and another that opposed it – for a resolution by the Plenum were rejected. The Parties then requested the EB of the CDM to undertake an assessment of the impact of including CCS in the CDM. At a meeting of the SBSTA in June 2009, the positions of CCS opponents and proponents were again shown to have hardened. While Canada, Australia, Kuwait and Nigeria were in favour of considering CCS under the CDM, Argentina, Brazil and Venezuela were opposed to it (Treber 2009). The points of contention in the negotiations are not only basic questions on the suitability of CCS as a technology to reduce greenhouse gases but also complex methodological and legal problems. De Coninck (2008) summarises the basic points of contention as follows:

- *Market readiness of CCS:* Those who oppose the use of CCS under the CDM argue that CCS has not yet achieved full market readiness and that the technology should not yet be funded within the flexible mechanisms. Proponents, on the other hand, focus on a learning-by-doing effect based on a strict body of rules and regulations because it could accelerate the technological development of CCS.
- *CCS should first be developed and tested in industrialised countries:* CCS opponents are afraid that offsetting a reduction in emissions through CCS under the CDM would offer an incentive to exploit developing countries as a test area for technology that may be unsafe. CCS proponents argue that it would give developing countries the opportunity to become important market players in the development and sale of the technologies involved.
- *CCS projects might displace other CDM projects:* Opponents are afraid that a large number of CCS projects would lead to a reduction in the market price for CERs. Brazil, one of the strongest opponents of considering CCS projects in the CDM, is still worried that its share of the CER market would fall as a result of including CCS projects because it has only little potential for the use of CCS, due to the high proportion of hydropower in its energy mix. On the other hand, it is pointed out that there would only be an incentive

for the use of the technology in the case of high allowance prices, owing to the high costs of CCS.

- *Technologies for the enhanced recovery of hydrocarbons do not contribute to a reduction in greenhouse gases:* CCS opponents argue that the approval of "enhanced oil recovery" (EOR) projects in which CO_2 is injected in the storage site to raise the oil production rate would lead to an increased consumption of oil, and therefore an increase in greenhouse gas emissions (as Luhmann also analysed in 2009). Proponents of CCS projects in the CDM counter that the additional volume of oil produced through EOR would also be used without incentives for CCS.
- *CCS would make the framework conditions for renewable CDM projects more difficult:* CCS opponents call for priority to be given to renewables in the reduction of greenhouse gas emissions. CCS proponents argue that the possibility of offsetting CCS projects under the CDM could encourage the Parties to adopt more ambitious targets to reduce greenhouse gases.

Referring to methodological aspects, the following issues are primarily discussed:

- *Project boundaries:* CCS technologies comprise several activities – capture, transport and storage. There is broad consensus between the Parties that all activities should be included in the CDM. However, it is not clear how to proceed if activities are carried out in countries with different statuses, i.e. if capture takes place in an Annex I country and storage in a non-Annex I country.
- *Offsetting additionally caused emissions ("carbon leakage"):* The term "carbon leakage" describes the offsetting of additional emissions caused within a CCS project. It was discussed between the Parties whether and how, for instance, emissions resulting from the increased coal requirements of a power plant due to efficiency losses in CO_2 capture could be offset. A second possible case would be to offset emissions resulting from the use of oil produced additionally through EOR in a CCS-CDM project.[9]
- *Permanence:* This aspect relates to the possibility that CO_2 could leak from the storage site after allowances for the achieved CO_2 reduction have been awarded. In order to guarantee a low degree of leakage of CO_2 and to be able to quantify leaked emissions, the Parties discussed guidelines for the selection and monitoring of storage sites. However, the duration of monitoring and how it is to be financed have not yet been stipulated. Moreover, it needs to be clarified how leaked emissions are to be offset.

2.2 Measures to reduce CO_2 in other branches of industry

Apart from CO_2 emitters from the area of power and heat generation, there are other sectors that release large quantities of CO_2 into the atmosphere. These branches would also be potentially suitable for capturing and storing this climate-changing gas. German industry, for

[9] In general, "carbon leakage" means the increase in emissions due to the displacement of industrial production (and hence emissions) from industrialised countries to those where no or fewer climate protection restrictions apply. This would lead to a decline in turnover and employment in the countries of origin. The initially lower emissions are then juxtaposed to higher emissions abroad (see http://www.co2-handel.de/article306_10147.html).

instance, which emits 160.7 million tonnes or 18.2 per cent of Germany's total CO_2 emissions (884.1 million tonnes of CO_2), is the country's third largest producer of CO_2 emissions after the energy industry (382.3 million tonnes of CO_2 = 43.2 per cent) and transport (167.4 million tonnes of CO_2 = 18.9 per cent) (DIW 2006). A CO_2 capture potential of 28 million tonnes per annum of large-scale industrial point sources was estimated for North Rhine-Westphalia, which corresponds to around 16 per cent of the total quantities of CO_2 that can be captured in NRW (WI 2009).

Tab. 2-3 List of known European CCS pilot and demonstration projects from other branches of industry (as of 9/2009)

Country/ Location	**Capture technology /branch of industry**	**Power output**	**CO_2 captured**	**Storage**	**Players**	**Commencement**
		MW_{el}	**Mt/a**			
France/ Florange	Post-combustion/steel	not specified	not specified	Saline aquifer	ArcelorMittal	not specified
Germany/ Eisenhüttenstadt	Post-combustion/steel	not specified	not specified	Saline aquifer	ArcelorMittal	not specified
Netherlands/ Barendrecht + Pernis	H_2 production/chemical industry + refineries	not specified	0.4	Depleted oil and gas fields	Shell	2011
Norway/ Bergen	Post-combustion/electricity + refineries	280 MW_{el} +350 MW_{th}	1.5	Saline aquifer	Gasnova	2014
England/ Scunthorpe	Post-combustion/ steel	not specified	not specified	Depleted oil and gas fields	Corus/Tata Steel	not specified
Norway/ Husnes	Post-combustion/other	400	2.5	Saline aquifer	Tinfos, Sor-Norge, Era-net, Sargas	not specified
Norway/ Karsto	Post-combustion/oil + gas refineries	420	1.2	Saline aquifer	Aker, Fluor, Mitsubishi	2012
Poland/ Kedzierzyn Kozle, Slaskie	Pre-combustion/ electricity +chemical industry	500 MW_{th} syngas+ 250 MW_{el}	3.4	Saline aquifer	PKE/ZAK	2014

Source: ZEP 2008 and authors' additions

Activities in other branches of industry (see Tab. 2-3) to reduce CO_2 emissions are primarily conducted in the *steel industry*. The EU-funded ULCOS programme (*U*ltra *L*ow *CO*$_2$ *S*teel-making) is an ambitious R&D programme to reduce process-related CO_2 emissions in the production of steel. The programme is currently in Phase II, in which several new steel production processes are being tested in pilot projects to examine the medium- to long-term most promising technologies on an industrial scale. The first technology to be evaluated on an industrial scale is based on blast furnace technology, including top gas recycling (TGR-

BF) and CCS. The ULCOS programme is supported by a consortium of 48 European partners[10].

The *cement industry* is also undertaking a long-term CCS research project via the European Cement Research Academy (ECRA). In the first phase, suitable capture processes for the clinker burning process were investigated. Oxyfuel and the post-combustion process via absorption were found to be particularly suitable. In the second phase, detailed technical and economic tests are being carried out for these two processes (ECRA 2007). Another project, being implemented by Associated Cement Companies Ltd. (ACC), aims to explore the use of biomass to fire kilns. In a special bioreactor, the CO_2 arising from the combustion process shall be used to produce oleiferous algae (Suri 2007).

In general, however, many other measures, such as raising energy efficiency, using new materials and lighter components and the increased use of secondary fuels (e.g. biomass), are being taken in "CO_2-intensive" branches of industry to reduce CO_2 emissions. (Schäfer 2009) mentions a number of examples of measures already taken in the cement industry to reduce CO_2 emissions:

- modernisation of existing furnaces
- substitution of old plants for new plants
- change to fuels that produce less carbon dioxide or (proportionately) biogenic fuels
- partial substitution of limestone by already calcined secondary raw materials
- replacement of cement clinkers by other main cement constituents.

Until now, no estimate has been made of the CCS potential for industrial point sources in Germany. However, CCS might possibly be necessary, since the CO_2 emissions from this sector, unlike the power and heat sectors, could not be completely avoided using efficiency measures and renewable energies. Against this backdrop, the German Advisory Council on the Environment calls for CCS at industrial point sources to have a higher priority over CCS in the power plant sector in the event of the construction of a CCS infrastructure (SRU 2009b).

2.3 Global networks

The most important CCS networks are briefly described below:

- *CO_2Net* was initiated by the 5th Framework Programme on Research and Development (FP) of the EU. It was set up in 2006 and is likely to be continued up to 2011. The network consists of a consortium of 30 large companies and organisations, mainly from the EU, but also from the USA and Australia. It focuses on combining the expertise from all CCS-relevant branches of industry, thus driving forward the advancement of the technology along the entire CCS chain.
- Thirteen geological institutes from seven European countries cooperate in *CO_2Geonet* to gain more detailed knowledge of geological deep structures in the area of geological

[10] For information on the ULCOS programme see also http://www.ulcos.org.

storage. This way, more precise information on storage capacity, storage site risks and recommendations on monitoring processes can be given.

- There is a very dedicated national network in the German Federal State of North-Rhine Westphalia (NRW): this is where the *Kompetenz-Netzwerk Kraftwerkstechnik (*Power Plant Technology Competence Network) was founded in 2005. Power plant builders, operators, suppliers, parts manufacturers, academia and research, the Energy Agency NRW (at that time the NRW State Initiative on Future Energies) and the Research and Energy Ministries of NRW are involved in this network. The aim of this network is to pool and coordinate the players' activities, and to act as an interface between business, academia and politics. At the same time, the network acts as an advisory body for the state government of NRW, and intends to initiate specific projects.

  The competence network is part of the field of power plant and network technology of the Energy Agency NRW. It consists of a high-ranking steering committee and subject-specific working groups that deal with specific issues, topics and projects. The two themes dealt with to date are

  - Advanced power plant technologies (700 degree power plant),
  - Options for future energy supply (low-carbon power plant).

3 Processes of CO_2 separation in electricity generation

3.1 New development trends and research and development activities in CO_2 separation processes

The processes to capture CO_2 can be subdivided into three technological groups: post-combustion processes, pre-combustion processes and oxyfuel processes (see Fig. 3-1).

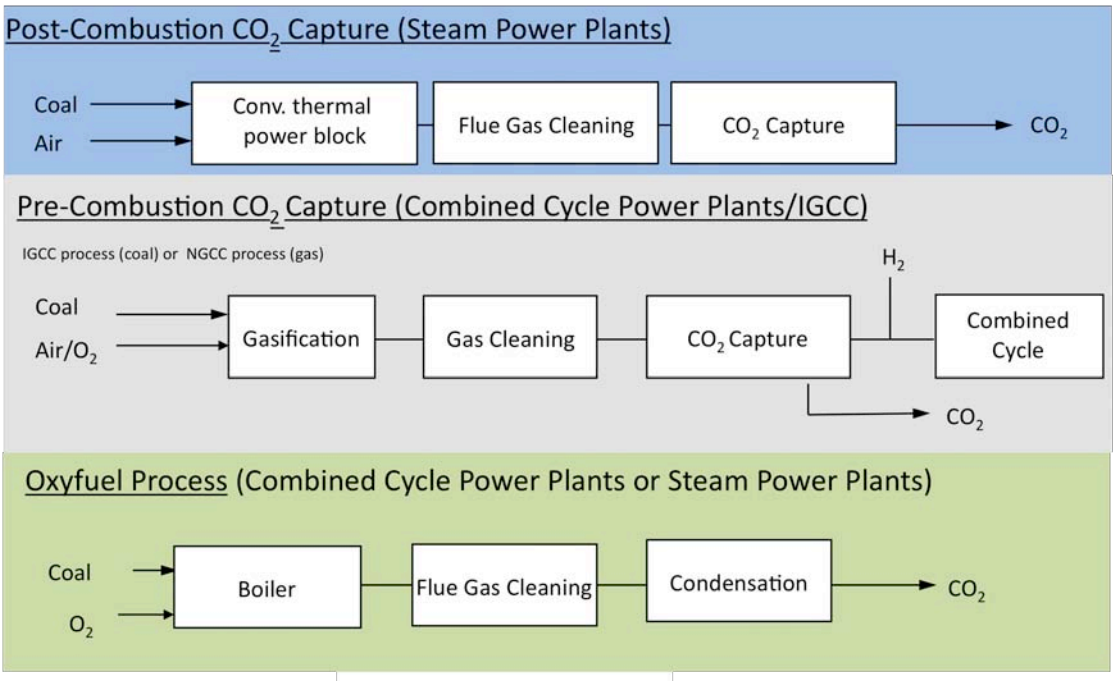


Fig. 3-1 Overview of various technological routes to CO_2 capture

Source: Ewers and Renzenbrink 2005

3.1.1 Post-combustion processes

In these processes, CO_2 is captured from the flue gas of power plants. The flue gas of conventional power plant processes has a CO_2 concentration of less than 15 per cent, because combustion of the fuel takes place with air, which is almost 80 per cent nitrogen. The low CO_2 concentration makes the economic capture of the greenhouse gas difficult, since a huge volume of gas needs to be treated, requiring large amounts of chemicals and energy. Nevertheless, compared with other capture processes, post-combustion processes have the highest short- to medium-term achievable potential for CO_2 reductions. This is because they are also suitable for being retrofitted onto existing power plants, which cause around two thirds of CO_2 emissions in the electricity sector (Figueroa et al. 2008). Demonstration plants are likely to be available by 2015, enabling the technology to be used on a large scale sometime between 2020 and 2025. In addition, post-combustion processes are increasing in importance because a broad market launch of Integrated Gasification Combined Cycle (IGCC) power plants with pre-combustion processes (see Section 3.1.2) have been curbed by a sharp increase in the investment expenditure for large-scale plants (Herzog et al. 2009).

Post-combustion processes are the most developed technological path to CO_2 capture, because similar scrubbing processes are already in use in other branches of industry. Some of the leading suppliers include Mitsubishi Heavy Industries (MHI; Japan), Cansolv (Canada), Fluor (USA), HTC Purenergy (Canada) and Aker Clean Carbon (Norway). Various technological paths are pursued within the category of post-combustion processes (see Tab. 3-1 for a detailed characterisation):

- *Absorption process:* The flue gas reacts with a solvent that absorbs CO_2. This group includes the most developed and common capture processes, such as amine gas treating, in particular. Monoethanolamine (MEA) is one of the preferred amine solutions. However, MEA is a relatively powerful solution that bonds strongly with CO_2, causing its regeneration to involve high energy use. For this reason, many current R&D projects are concentrating on searching for alternative or modified solvents. For instance, attempts are being made to increase their reactivity by modifying the molecular geometry of amine solvents ("hindered amines") or a combination of various solvents ("blended solvents").
- *Adsorption process:* CO_2 is not absorbed by the solvent but is attached to its surface. There is no chemical reaction between the CO_2 and the solvent. At present, work is being carried out on adsorption processes that use zeolitic or metal-organic substances to bond the CO_2. The former have a very high CO_2 selectivity, but a low capture capacity. The latter have a high adsorption capacity, but it is not sure how resistant it is to impurities in the flue gas.
- *Membrane process:* This process is an alternative and medium- to long-term option. Membranes are semi-permeable separating layers used to separate mixtures of substances, such as flue gas. They are already used commercially in a range of industries. Their use in CO_2 capture is still at a relatively early stage of development. Membranes have the advantage that impurities are removed by separating the flue gas prior to the capture process, reducing the consumption of the solvent. However, existing membrane technologies have a low level of technological maturity, and are not yet an economical option. For this reason, one area that current R&D projects are investigating is to improve the economic efficiency of the technology.
- *Biological capture processes*: These processes will also only be available on a large scale in the medium to long term. They use natural organisms, such as algae or enzymes, to bond the CO_2. Algae-based capture processes are currently being pursued with great interest in the USA, since CO_2 is being converted into biomass, which can be utilised as energy. German energy suppliers such as RWE and E.On and the Swedish state-owned enterprise Vattenfall are also working on similar projects. Until now, however, such capture processes have only been tested in pilot or laboratory settings. Also, algae cultivation in open ponds may require large areas of land. For this reason, intensive work on the development of closed reactors for algae cultivation is being conducted.

In Germany, E.On in particular is concentrating on developing post-combustion technology. E.On has a total of seven pilot projects which are either in the planning stages or are operational. In these projects, the company is cooperating with leading suppliers of scrubbing processes, plant builders and research institutions (E.On 2009):

- *Pilot plant Karlshamn (Sweden):* Since spring 2009, E.On, in cooperation with Alstom, has been operating a pilot plant based on a scrubbing process with chilled ammonia. Thirty tonnes of CO_2 are to be separated daily.
- *CATO pilot plant Maasvlakte (Netherlands):* Up to the end of 2008, a scrubbing process based on amino acid salts was tested at the E.On site Maasvlakte in cooperation with the Dutch research foundation TNO. Further operation of the pilot plant is being carried out within the CATO follow-up project CATO-2.
- *Pilot plant with Hitachi Power Europe and Electralabel:* Construction of a plant for the identification of a new, optimised solvent. The plant is designed to treat a maximum of 5,000 m^3 flue gas per hour. It should be operational for four years.
- *Pilot plant with Cansolv Technologies:* The capture process of the Canadian technology company is to be used here for the first time in Europe. In a two- to three-year test phase, it is intended to operate the plant with a flue gas volume of 20,000 m^3 per hour.
- *Pilot plant Staudinger (Germany):* Construction of a pilot plant within a research project together with Siemens, in which a new solvent for CO_2 capture is to be developed. The pilot plant went into operation in mid-September 2009.
- *Pilot plant Wilhelmshaven (Germany):* Optimisation of Fluor's capture technology (Ecoamine FG+). A pilot plant is expected to be operational in 2010 at the power plant site in Wilhelmshaven. The cost of the project amounts to approximately € 10 million.
- *Pilot plant with Mitsubishi Heavy Industries (Germany):* The plant is to be put into operation in 2010/11 at a power plant site yet to be determined. The latest capture processes by Mitsubishi Heavy Industries will be used in combination with advanced solvents. The plant is designed for 20,000 m^3 flue gas per hour.

Simultaneously with the pilot projects listed above, E.On is working in cooperation with higher education institutions and research institutions in Europe and North America to develop and enhance scrubbing detergents and scrubbing processes.

Tab. 3-1 New developments in post-combustion processes

Process	Description of process	Advantages	Disadvantages	R&D activities
Absorption				
Hindered amines	Modification of the molecular geometry of amines. The aim is to increase the reactivity of amines and to weaken the bond between amines and CO_2 in order to reduce the energy requirements involved in CO_2 capture.	Lower efficiency losses due to higher reactivity and the less complicated regeneration of the solvent.	The cost of the solvent production of amines is higher than conventional amine gas treating.	Mitsubishi Heavy Industry (MHI) has developed a modified amine called KS-1. The process is being used in four large-scale gas-fired power plants; four further plants are currently under construction. Use in coal-fired power plants is currently being tested on a pilot scale.
Blended solvents	Blending different solvents to optimise capture efficiency and the kinetics, as well as to enhance the reaction rate.	Blending inexpensive solvents with small quantities of expensive solvents lowers the overall costs of the capture process. An enhancement of the kinetics enables a smaller absorber size and therefore lower investment expenditure.	Substances frequently used for blending with solvents (promoters), e.g. piperazine or diethanolamine, are toxic and harmful to the environment. Alternative promoters are currently being investigated (Smith et al. 2008).	The Universities of Texas, Regina and Waterloo are currently conducting laboratory tests on blending piperazines (PZ) with other amines and carbonates (potassium carbonate; K_2CO_3).
Cansolv DC 101	The process is similar to conventional amine gas treating, but uses a new tertiary amine called DC 101.	The solvent is characterised by low energy consumption, low oxidation, a rapid reaction process and low investment, operating and maintenance costs. Other substances such as SO_2 or NO_x can be captured from the flue gas at the same time as the CO_2.	Not specified	The process was demonstrated in 2004 in a natural gas-fired pilot plant and in 2005 in a paper and pulp factory in Virginia (USA).

Process	Description of process	Advantages	Disadvantages	R&D activities
Chilled ammonia	Ammonium carbonate, which reacts with CO_2 to form ammonium bicarbonate, is used as the solvent in place of amines. After separation of the pure CO_2 stream, the residual bicarbonate is converted into carbonate. Prior to the capture process, the flue gas is cooled to a temperature of 0–10°C in order to prevent the toxic ammonia from escaping and to achieve a high capture level.	Considerably lower energy intensity than conventional amine gas treating.	Risk of the escape of toxic emissions of ammonia.	The process was originally developed by Nexant, and is being licensed by Alstom. The process is being tested by American Electric Power (AEP) in a power plant in New Haven, West Virginia, and by E.On in a pilot plant in Karlshamn, Sweden (E.On 2009).
Dry regenerable sorbents	A variety of solids can be used to absorb and then release CO_2. The Research Triangle Institute (RTI) is developing a capture process on the basis of sodium carbonate (Na_2CO_3), which reacts with water and CO_2 to form sodium bicarbonate ($NaHCO_3$).	Suitable for retrofitting existing plants. Capture rates of over 90% are possible. Lower capital costs and energy requirement than conventional amine gas treating.	Solid solvents are more difficult to handle than fluid solvents. The reaction rate between CO_2 and $NaCO_2$ is very high and creates considerable heat, which is why an efficient transfer and process integration of the heat is required. So far, no CO_2 capture processes have been employed large-scale on the basis of solid solvents.	RTI started to carry out tests on the process in 2002. Several solvents and reactor designs have been tested.
Ionic liquids	Organic salts are used as CO_2 solvents in a liquid, ionic state under	Due to the weak bond between the salts and the CO_2, the regeneration of the sol-	The salts that, to our current knowledge, are most suitable for CO_2 capture have so far only	The process is being researched at the University of Notre Dame, Indiana, in cooperation with experts from the U.S. NETL (National

Process	Description of process	Advantages	Disadvantages	R&D activities
	ambient conditions. The salts capture the CO_2 from the flue gas through a weak ionic bond.	vent requires relatively little energy. High thermal stability of the salts at temperatures of >200°C (Anderson et al. 2007). The salts are also suitable for capturing SO_2.	been produced in small quantities and at high cost. Unlike conventional solvents, the salts have a high level of viscosity. This can lead to higher energy intensity within the process. Further research is required into this matter.	Energy Technology Laboratory). The properties of various salts and their use in combination with membranes is being investigated.
Carbonate looping	The CO_2 contained in flue gas reacts in a carbonator with burnt lime (CaO) to form limestone ($CaCO_3$). The CO_2 is then leached out of the limestone at temperatures of 850–920°C in a regenerator, leaving behind burnt lime (CaO). The CaO can be used for another reaction with CO_2.	The process can be retrofitted onto existing power plants. The extracted lime can then be used in processes for the desulphurisation of flue gas. Additional heat is formed in the reaction of CaO and CO_2 that can be used to dry the fuel or produce steam, for instance.	After carrying out several reaction runs, the absorption capacity of the $CaCO_3$ decreases successively due to increasing solidification resulting from heating during the process. Fresh $CaCO_3$ must constantly be added to ensure a continuously high capture rate. Leaching out CO_2 from the limestone is an endothermic reaction during which heat must be supplied. The heat is preferably produced by combusting coal with oxygen, since combustion with air reduces the concentration of the CO_2 stream. Around one third of the coal supply is used in the process due to the high energy intensity of O_2 production.	An experimental field on a 1 MW_{th} scale is currently being established at Darmstadt University of Technology to carry out tests on the technological realisation of the process (Epple et al. 2008).

Process	Description of process	Advantages	Disadvantages	R&D activities
Adsorption				
Zeolites	Zeolites are highly porous materials with a crystalline molecular structure. Due to their crystalline structure, they are well suited for the adsorption of CO_2.	Zeolites have a relatively high selectivity for CO_2 and N_2.	Zeolites have a low capture capacity. The capture performance is impaired by the presence of water vapour.	CO_2 capture on the basis of zeolites was tested in a variety of pilot trials conducted by the Tokyo Electric Power Company (TEPCO) in the 1990s and at Carnegie Mellon University.
Metal-organic frameworks	Metal-organic frameworks are porous, crystalline solids with a structure resembling zeolites. They are made of metal ions, and have a high capacity for the adsorption of CO_2. Over 600 different metal-organic frameworks have been developed in recent years.	High capacity for the adsorption of CO_2. Low heat requirements to separate CO_2 from the solvent.	The stability of the substances towards flue gas has yet to be tested under process conditions. The impact of impurities in the flue gas on the structures has yet to be researched.	The research activities of the U.S. Department of Energy (DOE) are led by the University of Phoenix (UOP). Among other things, the UOP has developed a model to identify metal-organic frameworks that comply best with the technical and economic requirements of the DOE.
Membrane process				
Polymer-based, ceramic, metal-based membranes	The flue gas is directed through membranes to separate the gas. Porous membranes are used to capture CO_2 from the flue gas. The CO_2 is then absorbed by amine solvents.	Due to the separation of the flue gas prior to absorption, no impurities can come into contact with the solvent, reducing the amount of solvent consumed.	Current technologies are characterised by poor membrane selectivity, a low level of technological maturity and high costs.	Current R&D activities deal with CO_2 selectivity, permeability and the enhancement of the economic efficiency of membranes. Moreover, several establishments, including the University of New Mexico, New Mexico Institute of Mining and Technology and Membrane Technology & Research (MTR), are carrying out research into alternative membrane designs. In Germany, Forschungszentrum Jülich is working on the development of porous and

Process	Description of process	Advantages	Disadvantages	R&D activities
				ceramic membranes and on suitable methods for the production of membranes.
Biological processes				
Enzyme-based capture systems	The CO_2 is bound by enzymes in a biological reactor and transformed into bicarbonate ions. The bicarbonate can then be processed into limestone, among other things.	The CO_2 is absorbed at low temperatures. The process is therefore considerably less CO_2-intensive than post-combustion processes.	The process is still at an early stage of development. Stable operation over a longer period and on a large scale has not yet been tested.	The Canadian company CO_2 Solution is developing and testing bacteria for the production of suitable enzymes in cooperation with Babcock and Wilcox. The company Carbozyme is developing and testing an enzyme-based capture process on a laboratory scale.
Algae-based capture systems	Algae cultures bred in open ponds or closed reactors are added to the captured CO_2. The CO_2 is transformed into air by photosynthesis. The algae reproduce and can be processed into biodiesel, for instance.	The CO_2 is transformed into biomass, which can be used as energy.	Open ponds for algae cultivation are associated with high space requirements; closed reactors require high investments (Rasmussen 2008). Very large amounts of algae are required to bind CO_2 emissions from coal- and gas-fired power plants. Harvesting algae for further use involves high energy requirements.	E.On has been operating a pilot plant in Hamburg since 2008 that transforms CO_2 into a specially developed micro alga. E.On and the City of Hamburg bear half of the costs of the pilot plant (€ 1 million) each. In cooperation with Jacobs University Bremen and Forschungszentrum Jülich, RWE is researching algae production assisted by fertilisation with flue gas containing CO_2. Lausitz University of Applied Sciences (FHL) has been commissioned by Vattenfall Europe to develop a concept for an algae breeding plant. The aim of the project is to build a pilot plant at Senftenberg combined heat and power plant on the basis of the knowledge gained. In the process, CO_2 from the flue gas of the power plant shall be converted into organic compounds by algae using photosynthesis (Vattenfall Europe 2009c). Two Canadian companies, Trident Exploration and Menova Energy, have been devel-

Process	Description of process	Advantages	Disadvantages	R&D activities
				oping a new reactor model for algae-based CO_2 capture since 2007 (Green Car Congress 2007). In May 2009, the company BioProcessAlgae received US$ 2.1 million from the U.S. State of Iowa to develop a bioreactor that uses the CO_2 emissions of an ethanol plant for algae production.

Source: Herzog et al. 2009, Figueroa et al. 2008, EPRI 2007

RWE is focusing on developing the post-combustion variant as an option for retrofitting existing power plants. RWE launched a pilot plant in August 2009 to scrub CO_2 at the power plant site in Niederaußem. The plant intends to separate 300 kg of CO_2 per hour and to achieve a capture rate of 90 per cent. The project is being conducted in cooperation with Linde and BASF (Ewers 2008), and is 40 per cent subsidised by the German Federal Ministry of Economics and Technology. RWE has ring-fenced a budget of around € 80 million for the entire project (Spiegel Online 2009). In addition to the German pilot plant, RWE is involved in developing two pilot plants in the USA to capture CO_2 from power plant flue gas. The plants have capacities of 3 MW_{el} and 20 MW_{el}, and are being constructed under the auspices of the Electric Power Research Institute (EPRI) and American Electric Power (AEP), respectively.

Vattenfall Europe intends to retrofit a boiler with a post-combustion process at the existing lignite-fired power plant Jänschwalde in Lusatia. The power plant consists of two boilers with a capacity of 250 MW_{el} each. Initial feasibility studies have already begun. It should go into operation in 2015 (Vattenfall Europe 2009a).

3.1.2 Pre-combustion processes

In these processes, the fuel is transformed by gasification into a synthesis gas consisting mainly of carbon monoxide (CO), hydrogen (H_2) and CO_2. The proportion of CO content of the synthesis gas is reduced in a shift reactor, creating a gas with a considerably higher CO_2 concentration than in the flue gas from conventional power plants. The CO_2 can be separated with considerably less energy consumption than in post-combustion processes. Despite their comparatively efficient methods of capture, pre-combustion processes have been a lower priority for R&D recently. This is explained by the fact that the distribution of IGCC power plant technologies has not yet extended beyond individual demonstration plants due to the high investment expenditure involved, amongst other things. In addition, developing countries are concentrating primarily on conventional combustion processes in the construction of new coal-fired power plants (Herzog et al. 2009). In Germany, RWE had intended to build an IGCC power plant with CO_2 capture by 2015. The anticipated gross performance of the power plant was 450 MW_{el} and the net performance around 330 MW_{el}. Approximately 2.6 million tonnes of CO_2 were to be captured annually (Ewers 2008). However, future plans were halted in November 2009 (see Section 2.1.1).

Current R&D activities in the field of pre-combustion deal primarily with the development of *new physical solvents* such as lithium silicate or alternative processes such as *membrane systems* or *chemical looping combustion (CLC).* In the latter, metal oxide, rather than oxygen, is used to oxidise the fuel. In this way, any direct contact between the fuel and air is avoided in the combustion process in order to create a concentrated CO_2 stream. The process is currently being pursued by European players in particular, such as Alstom and the Swedish Chalmers University.

Tab. 3-2 shows a detailed characterisation of various approaches of this process.

Tab. 3-2 New developments in pre-combustion processes

Process	Description of process	Advantages	Disadvantages	Projects/licensed processes
New physical solvents	The Research Triangle Institute (RTI) is currently developing a solvent on the basis of lithium silicate (Li_4SiO_4) to capture CO_2 at high temperatures and under high pressures.	The performance of the solvent is not negatively affected by high temperatures, pressures of 0–20 bar, CO_2 concentrations of 2–20% or impurities in the synthetic gas stream.	The process has not yet been tested on a large scale, but such tests are being planned.	In 2007, RTI successfully tested the process on a laboratory scale. A pilot plant with a daily capture performance of 1 tonne of CO_2 should be put into operation by 2010, followed by a large-scale demonstration plant with a capture capacity of 100 tonnes/day by 2013 (Gupta 2009).
Polymer-based membrane systems	The process is based on the various permeabilities of the components of syngas. Synthesis gas passes through several polymeric membranes with various permeabilities, enabling CO_2 to be captured from the synthesis gas.	Membrane technologies do not require any phase changes in the process. They involve low maintenance costs.	The stage of development is close to commercialisation, but the costs are still very high.	The U.S. Department of Energy is financing a variety of R&D projects on membrane processes, one of which is the development of a liquid membrane that is stable at high temperatures and has a high CO_2 selectivity.
Chemical looping combustion (CLC)	Metal oxides or limestone-based oxygen carriers are used instead of oxygen to oxidise the fuel. Direct contact between the fuel and the air supplied for combustion is therefore avoided. The resulting combustion exhaust gases consist mainly of CO_2 and water, making it easy in the oxyfuel process to separate the CO_2 once the water has been condensed out.	The process does not require any energy-intensive production of oxygen in air separation plants. The high concentration of CO_2 in the combustion exhaust gas reduces the energy required to capture CO_2 compared to post-combustion systems.	The process is still at an early stage of development, and is currently being tested on the pilot scale. So far, the process is only suitable for gaseous fuels. Solid fuels such as coal must be gasified first.	The process was tested for over 100 operating hours in 2004 in a 10 kW_{th} pilot plant of Chalmers University in Göteborg. Alstom, in cooperation with Chalmers University, is currently developing and testing a limestone-based CLC process for new and existing coal-fired power plants (Andrus 2009). A 1 MW_{th} test plant is currently being constructed at Darmstadt University of Technology to test the technical feasibility of CLC in coal-fired plants (Epple et al. 2008). Various reactor concepts and oxygen carriers are being tested within the ENCAP project to make the process exploitable for both gaseous and solid fuels (ENCAP 2009).

Source: Authors' design

3.1.3 Oxyfuel processes

In oxyfuel processes, virtually pure oxygen (over 95 per cent) is used in place of air for the combustion of fuel. In this way, the CO_2 concentration in the flue gas can be increased to 80 per cent, enabling CO_2 to be captured by simply condensing it out. Oxyfuel processes are considered to be a promising alternative to post- and pre-combustion processes, but are still at an early stage of development. So far, virtually no reliable economic feasibility studies have been conducted.

In Germany, Vattenfall Europe, in particular, is concentrating on the area of oxyfuel technology. The company put the world's first pilot plant (30 MW_{th}) for lignite combustion with the oxyfuel process into operation in September 2008 at the Schwarze Pumpe site in the Brandenburg town of Spremberg. The cost of the plant amounts to around € 70 million (Vattenfall Europe 2009b). In addition, Vattenfall Europe is conducting feasibility studies for the installation of a 250 MW_{el} oxyfuel power plant at the plant site of Jänschwalde in Lusatia. The oxyfuel boiler will replace a conventional boiler, and will be commissioned in 2015 (Vattenfall Europe 2009a).

Current R&D work, for example, that by Babcock & Wilcox on oxyfuel technology, explores energy-efficient methods for producing the required oxygen. Although cryogenic air separation processes are currently being used for this purpose, they are very energy- and cost-intensive. They make up around 33 per cent of the investment expenditure and 67 per cent of the power demand of an oxyfuel plant (ENCAP 2009). Alternative options to oxygen production are *ceramic membrane systems* and *molecular sieves* or the *adsorption of oxygen*. In the process, the mineral perovskite, a calcium titanium oxide ($CaTiO_3$), is used for the adsorption and storage of oxygen. With the support of the U.S. Department of Energy, Linde is currently building a suitable pilot plant with a production output of 0.7 tonnes of oxygen per day. Linde is also exploring the cost effectiveness of the process in cooperation with Alstom.

Tab. 3-2 shows a detailed characterisation of various approaches of this process.

Tab. 3-3 New developments in oxyfuel processes

Process	Description of process	Advantages	Disadvantages	Projects/licensed processes
Optimised processes for cryogenic air separation	In the oxyfuel process, pure oxygen is used in place of air for the combustion of fuel. A flue gas consisting mainly of CO_2 and water vapour is created. The most commonly used method to produce oxygen is cryogenic air separation (distillation), whereby the oxygen is separated from the other gas components of air.	Unlike pre-combustion systems, oxyfuel processes can be used in new and existing conventional power plants. Air separation processes are already used on a large scale in a variety of industrial sectors.	Compared to post- and pre-combustion processes, the oxyfuel route is still at an early stage of development. Air separation processes are very cost- and energy-intensive. They make up approximately 67% of the power required in oxyfuel processes, reducing the cost effectiveness of the process.	Babcock & Wilcox is working on a cost-effective oxyfuel process suitable for retrofitting existing plants (Figueroa et al. 2008). Alstom Power is working on an optimised boiler design for combustion with pure oxygen. In September 2008, Linde AG and Vattenfall Europe Technology Research entered into a technology partnership to develop oxyfuel technology on the basis of lignite. For this purpose, a pilot plant was put into operation in Lusatia. Linde is providing the air separation technology. In 2015, a 250 MW_{el} oxyfuel demonstration power plant is to be commissioned at the Jänschwalde site in Lusatia (Vattenfall Europe 2009b). Intensive research is currently being undertaken into more efficient air separation plants. For instance, a number of industrial gas producers are working towards optimising heat exchangers, high-capacity compressors and control systems (Dechema 2009).
Ceramic membrane systems and molecular sieves	In place of cryogenic air separation, air is passed through ceramic membranes or molecular sieves at high temperatures (800–900°C). In the process, oxygen is separated from the remaining gas components of air.	OTM technology is able to increase the efficiency of the oxyfuel process compared to oxyfuel processes based on cryogenic air separation by 4.6% (Hassel et al 2008).	The technology is at an early stage of development and has not yet been tested on a large scale.	The “ion transport membrane” system (ITM) by Air Products and Chemicals is the furthest developed method in the sense of commercial use. This system is based on patented high-temperature ceramic membranes. Air Products has been operating a pilot plant since 2005; another plant should go into operation this year (Dechema 2009).

Process	Description of process	Advantages	Disadvantages	Projects/licensed processes
				Praxair has also developed a transport membrane system. The enterprise is currently working on integrating the individual process components and on the fuel flexibility of the process. The R&D activities have received US$ 5.4 million in funding from the U.S. Department of Energy (Hassel et al. 2008).
Ceramic autothermal recovery (CAR)	Air is fed at high temperatures to a fixed bed vessel filled with pellets made of perovskite ($CaTiO_3$). Oxygen is absorbed and stored at the surface of the perovskite.	The adsoption of oxygen on perovskite takes place exothermically, and therefore requires no or little heat input. According to an initial cost-efficiency analysis by Linde and Alstom, the CAR process is more effective and less expensive than cryogenic air separation processes (Dechema 2009).	The process is at an early stage of development, and has not yet been tested on a large scale. Problems have yet to be solved with regard to the effectiveness and cost of perovskite, as well as its behaviour towards impurities (Dechema 2009).	With the assistance of the U.S. Department of Energy, Linde has been advancing the process in the past two years. Linde is building a pilot plant for 0.7 tonnes of oxygen/day in order to test the technology in collaboration with Western Research Institute. Together with Alstom Power Plant Laboratories, Linde is compiling a detailed cost-efficiency analysis for an oxyfuel plant that uses the CAR process. Western Research Institute (WRI) is testing the CAR process in a pilot plant.

Source: Authors' design

3.2 Retrofitting power plants

3.2.1 The term "capture ready"

Retrofitting occurs when existing power plants are supplemented at a later date by a further known component, or one that is yet to be developed, so as to be able to fulfil an additional task without seriously restricting the function of the existing plant. "In so doing, not only unavoidable (but if possible limitable) restrictions of the function in the retrofitting phase (long shut-downs can be very costly), but also those that can arise in the regular operation of the plant after retrofitting have to be taken into consideration," (Fischedick et al. 2006).

If the retrofit of a power plant involves capturing CO_2 emissions, this can be defined as CO_2 retrofitting. If possible future CO_2 retrofitting is taken into consideration when power plants are being planned and constructed, these plants are generally called "capture ready" power plants. Such designs should at least decrease the retrofitting effort and are expected to be more efficient than in the case of unprepared retrofitting (Fischedick et al. 2006). With plants that are not "capture ready", the retrofit of CO_2 capture technologies leads to either higher costs and efficiency losses or cannot be carried out due to lack of space at the plant site. "Capture readiness" is a central focus of the EU "CCS Directive" because only such power plants will be granted planning permission in the future (compare Section 6.1.2.6).

So far, there is no common understanding of the meaning of the term "capture ready". The most commonly cited definition was coined by the International Energy Agency (Irons et al. 2007). According to this definition, in order to achieve the status of "capture ready", the following criteria must be met:

- *Provision of space:* Not only additional equipment with scrubbers, CO_2 compressors, oxygen production plants, etc. need to be taken into account; further space may also be required for the construction of a whole additional power generation plant to compensate for the efficiency losses that would occur in the post-combustion method.
- *Identification of transport routes:* This requires potential CO_2 storage sites, their capacities and distances from the power plants to be identified at the preliminary stage. The next stage would be to identify potential transport routes. If pipelines are intended, potential obstacles such as securing rights of way and also projections of public reaction must be evaluated. In the event of transportation by ship, the feasibility, safety and acceptance of on-shore buffer storage and ship loading and unloading facilities must be assessed.
- *Storage sites*: The requirements for identifying and qualifying storage sites must be defined by policy-makers. According to the IEA, it is conceivable, on the one hand, to simply prove the existence of a storage reservoir with sufficiently large capacity; on the other hand, it could be necessary to carry out a detailed geological analysis and to reserve the option for a certain storage capacity at an early stage to avoid the intended area being used for other purposes.
- *Pre-investments:* A multitude of pre-investments are listed and economically assessed for the different capture routes. The IEA provides member countries of the Greenhouse Gas Programme with a tool to calculate and assess pre-investments.

In a study by Ecofys and MVV Consulting (Graus et al. 2008), a survey of power plant operators was conducted, which investigated how many existing and planned fossil-fuel fired power plants in the EU are “capture ready”. The study takes only gas- and coal-fired power plants with capacities >300 MW into account. This includes approximately 260 power plants with a total capacity of 200 GW, or 25 per cent of the European power generation capacity. A total of 31 operators of planned gas-fired power plants or plants under construction, as well as 16 operators of planned coal-fired power plants or plants under construction took part in the survey. Fig. 3-2 shows the share of “capture ready” plants of the surveyed operators’ gas- and coal-fired power plants currently being planned or under construction. No information is available on 118 planned gas-fired power plants or plants under construction and 48 coal-fired power plants currently being planned or under construction. The diagram reveals that the majority of gas-fired power plants currently being planned or under construction are not designed to be “capture ready”. The requirements of CCS technology have been taken into greater consideration among the investigated coal-fired power plants (13 of the 16 power stations). In both cases, however, the significance of the survey is limited, due to the large number of power plants for which no information was available.

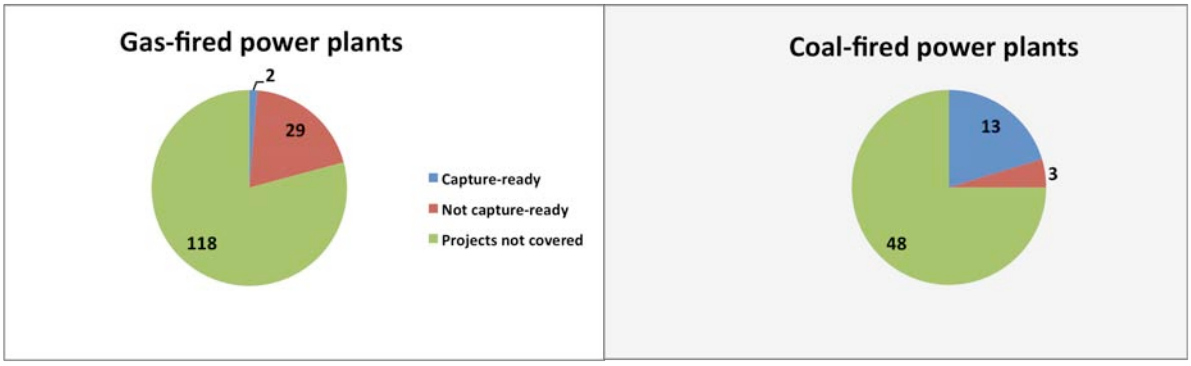


Fig. 3-2 Number of “capture-ready” and “not capture-ready” power plants recorded in a survey

Source: Based on Graus et al. 2008

In the study, power plants that met the following conditions were classified as “capture ready” (Graus et al. 2008):

- implementation of a feasibility study for the retrofit of CO_2 capture technologies,
- availability of sufficient space for the required CCS technology during the construction and operation of the plant,
- assessment of the plant components that would require adjustment in the event of a retrofit,
- assessment of potential pre-investments,
- evaluation of the potential storage site and a suitable transportation route to the storage site.

The criteria applied are therefore more or less identical to the aforementioned points. Fig. 3-2 illustrates the proportion of “capture ready” power plants to such power plants unsuitable for retrofitting. It is clear that preparations for retrofits onto coal-fired power plants are much more advanced than those for gas-fired power plants.

In Germany, TÜV NORD has developed “a binding catalogue of requirements for carbon capture readiness”. The requirements for “carbon capture ready” certification are summarised in the TÜV NORD Climate Change Standard TN-CC 006, and aim to offer a “clear definition of the term” (TÜV NORD CERT 2008). At present, however, these requirements have not been agreed upon in either Germany or abroad; furthermore, certification is voluntary since it has not yet been required by law. For this reason, certification is only related to plans for power plants. Amongst other things, it must be proven that

- the location is generally suitable for retrofitting the power plant by 2020, and that sufficient space is reserved for the refit;
- adjustments already carried out to the power plant for later retrofitting do not have a negative impact on efficiency, and
- a site-specific concept has been presented regarding the transportation and long-term storage of the captured CO_2.

In 2008, the first two power plant plans by E.On (Wilhelmshaven and Antwerp) were awarded the certificate (BSOZD 2008).

3.2.2 Measures for and effects of refits for CO_2 capture

There are various requirements for potential retrofitting, depending on the capture process.

Tab. 3-4 summarises which individual steps have to be implemented with the various processes.

Regardless of the chosen capture routes, the following general impacts of retrofits can be determined:

- *Efficiency:* The efficiency of “capture ready” plants is generally lower than the potential efficiency of new plants with CO_2 capture. In a study for the Federal State of North Rhine-Westphalia, an additional efficiency loss of 1-2 percentage points was assumed with retrofits in consultation with energy suppliers (WI 2009).
- *Increased investment expenditure:* Retrofitting leads to increased investment expenditure. However, these can be offset over a shorter period than over the total lifetime of the power plant. CO_2 retrofitting is, therefore, only practical if the plant has a sufficiently long remaining service life.
- *Retrofit phase:* During the retrofit phase, the power plants must be shut down temporarily. As a result, they cannot generate any revenue during the refit.
- *Additional space requirements:* Space has to be provided not only on the premises of the power plant, but also within the plant to be able to integrate the CO_2 capture plants or to make any necessary alterations. Estimates assume 50 per cent more space for natural gas combined cycle power plants and up to 200 per cent for conventional coal-fired power plants (Fischedick et al. 2006).

Tab. 3-4 Measures to be carried out in various CO_2 capture processes

Post-combustion	Installation of a CO_2 gas scrubber Installation of a CO_2 liquefaction plant Connections for heat extraction to regenerate the scrubbing agent Optimisation of the cooling system Provisions for heat recovery in CO_2 capture and liquefaction Plants to remove the liquefied CO_2 Optimisation of the flue gas desulphurisation plant to minimise the SO_2 content in the flue gas Adjustment of the pipeline system Provisions for the power plant's own electricity requirements Higher thermal power requirements in the form of cooling energy
Pre-combustion *)	Installation of a natural gas reformer Installation of a CO_2 gas scrubber before the gas turbine combustor The gas turbine combustor must be retrofitted to enable H_2 to be used as fuel Installation of a CO_2 liquefaction plant Plants to remove the liquefied CO_2
Oxyfuel	Installation of an air separation plant Installation of a CO_2 liquefaction plant Retrofit or replacement of the existing steam generator Increase of the cooling capacity to enable the water to be condensed out of the exhaust gas It has to be guaranteed that the CO_2 pipeline is highly corrosion-resistant to O_2 and SO_2 components in the liquefied CO_2
*) *Retrofitting existing natural gas combined cycle power plants*	

Source: Fischedick et al. 2006

A project carried out by the research association ef.Ruhr between 2007 and 2009 entitled *"Analyse zur Nachrüstung von Kohlekraftwerken mit einer CO_2-Rückhaltung"* (Analysis for the retrofitting of coal power plants with CO_2 capture) investigated how to plan retrofitting coal-fired power plants with CO_2 capture. The project simulated the influence of various concepts of retrofitted CO_2 scrubbers on the power plant operation using the example of the "hard coal reference power plant NRW". In addition, various approaches to separate, prepare, liquefy and transport CO_2 were explored. (ef.ruhr 2009)

Around the same time as this technically-oriented project, in a study (WI 2009) Wuppertal Institute analysed which power plants would generally be suitable for CO_2 retrofitting in North Rhine-Westphalia, what impact a CCS strategy would have on the federal state's carbon footprint and what infrastructure would be required for transportation and storage (see also Section 10.7).

4 Analysis of the options for the use of CO_2

4.1 Reuse of CO_2

We will now give an overview of the possibilities for reusing CO_2.

Chemical substances/hydrocarbons: Carbon dioxide is already employed as a parent substance to produce a variety of materials, ranging from the chemical raw methanol to end products, such as urethane, tensides and urea. Of these end products, urea has the highest market volume. The annual global demand for urea is around 90 million tonnes. A total of around 10 million tonnes of inorganic and organic carbonates are required annually. Polyurethane also has a market volume of 10 million tonnes (IPCC 2005). Putting these figures into proportion, however, the CO_2 energy-related emissions alone were 31 billion tonnes worldwide and 790 million tonnes in Germany (BMWI 2008b).

Technical aids: Carbon dioxide is also used as a technical aid in dry cleaning, fire extinguishers, aerosol cans and cooling devices, along with other applications. This potential could be replaced at very short notice by CO_2 captured from carbon-emitting power plants or other CO_2-emitting industrial facilities. Compared with the quantity of CO_2 created from power plant processes, however, the market potential is tiny. In addition, the majority of these processes are brief since the CO_2 is released again very quickly. According to (IPCC 2005), the worldwide demand for the technical use of CO_2 is around 10 million tonnes.

Food: In the food industry, CO_2 is mainly used as carbon dioxide gas in beverages and to neutralise water. In terms of volume, the possibility of substituting CO_2 used in this industry with captured CO_2 is virtually negligible. The purity requirements and binding periods are also reasons for this not being pursued. The advantage of these approaches, however, is that the natural underground occurrence of CO_2 is not tapped, avoiding unnecessary additional emissions. Around 8 million tonnes of CO_2 are used worldwide in the food industry each year (IPCC 2005).

Fig. 4-1 shows the possibilities of recycling CO_2, and Tab. 4-1 summarises the current global industrial applications of CO_2. This data shows that the current level of applying CO_2 is comparatively low.

Previous estimates assumed that between much less than 1 per cent and a maximum of 5 per cent of the current quantity of CO_2 produced can be bound to product cycles (IPCC 2005, Plass 2002). Accordingly, today's total worldwide industrial demand for CO_2 is around 115 million tonnes of CO_2/a (around 72 per cent of which (65 million tonnes) is used in the production of urea). This figure corresponds with around 0.5 per cent of annual energy-related CO_2 emissions worldwide. It must also be taken into account that CO_2 is not bound long-term when reused. The "binding periods" vary from a few weeks (for methanol, for instance) to several decades (for various plastics, for example). Furthermore, binding separated CO_2 (and the energy expenditure associated with it) may not necessarily be more favourable to the energy and emissions reduction balance than the conventional method of binding carbon as "feedstock" in the chemical process.

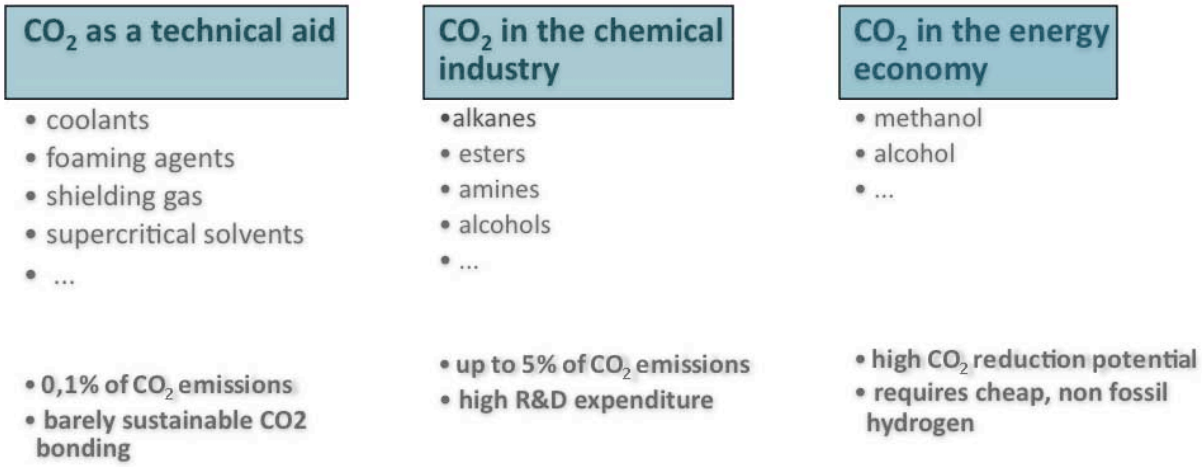


Fig. 4-1 List of possibilities for using CO_2 in the technological, chemical and energy sectors

Source: Plass 2002

The maximum potential of 5 per cent given in Fig. 4-1 is based on the assumption that previous common methods and areas of application continue to be used. As shown later in connection with the synthesis of methanol, use of CO_2 as a "raw material" would be significantly different once "cheap, non-fossil hydrogen", for example, or other reducing agents become available, enhancing the potential for reduction. Plastics could then be used on a much larger scale as substitutes for other materials, such as those used in the metal sector (including the manufacture of car bodies).

Tab. 4-1 Current global industrial applications of CO_2 (only products and applications in the megatonne region; figures should be viewed with caution)

	Total market volume	**CO_2-based market volume**	
	Mt/a	Mt/a	%
Urea	90	65	72
Methanol (in addition to CO)	24	< 8	< 33
Inorganic carbonates	8	3	38
Organic carbonates	2.6	0.2	8
Polyurethanes	10	< 10	< 100
Technical use	10	10	100
Food industry	8	8	100

Source: IPCC 2005

We will now give a number of examples of additional possibilities for future use:

Plastics: Plastics consist of macromolecules – long carbon chains – that can also contain other elements, such as hydrogen, oxygen, nitrogen and sulphur. These macromolecules can be produced from smaller molecules by synthesis or from natural products by chemical conversion.

Around 4 per cent of petroleum products from refineries is currently used to produce synthetic plastics (n-21 2010). After the oil has been broken down into short-chain hydrocarbons, these are joined together in the plastic synthesis to make the longest possible carbon chains.

In place of crude oil, short-chain hydrocarbons that act as the base material can be created from CO_2. With this method of reusing CO_2, further development is required only in the conversion of CO_2 into different hydrocarbons.

Initial research findings have been presented on the manufacture of plastics from natural products using CO_2. One such example is the manufacture of plastics using limonene: at Cornell University in Ithaka, a catalytic process has been developed in a laboratory setting. In this process, robust plastic resembling polystyrene is created out of CO_2 and a substance called limonene, which can be found in orange peel. Processes such as these, however, are still at an early stage of development (Froboese 2007).

An aside: Innovative building material

A scientist from the field of biomineralisation, Professor Brent Constantz from California, has developed a process that enables CO_2 captured from power plants and waste heat to be used to produce cement. In the process, the flue gases from the power plant pass through huge seawater tanks. The magnesium and calcium dissolved in water forms carbonates with the carbon dioxide, creating a mineral sludge that can be dried using waste heat from the power plant, which would otherwise remain unused. It is questionable, however, whether these processes can be adapted to an industrial scale, how lucrative they might be, and how rapidly new developments can be integrated into existing processes and accepted by their respective sectors (Biello 2008).

Fuels: The C atom cannot only be reused in substances. In certain conditions, a further dual use of the carbon atom is also conceivable, i.e. a lower emission of CO_2 per energy quantity. In this case, the captured CO_2 is not stored, but further processed into methanol, for instance, using CO_2-free hydrogen obtained from wind energy, for example, or, as is being considered in the USA, from nuclear power. The product created (in this case methanol) is reused as energy. Processes to create methanol are largely founded on the base material being converted first into a synthesis gas and subsequently into methanol (CH_3OH).

Synthesis gases for a methanol synthesis, consisting of CO, CO_2, hydrogen (H_2), residual methane and inert gases, are produced conventionally on the basis of natural gas or coal. In other processes, however, synthesis gases can also be produced from a mixture of CO_2 and H_2 from other processes (for example, CO_2 as a separation product of an integrated coal gasification and H_2 on the basis of electrolytic processes) and then specifically used for the synthesis of dimethyl ether (DME), synthetic fuels (gas-to-liquid) or methanol.

In the case of methanol as the target product, a non-conventional process can be applied in which synthesis gas, consisting of only CO_2 and H_2, is converted into methanol and water in a heterogeneous catalysed reaction system:

(A) $CO_2 + H_2 \leftrightarrow CO + H_2O$ 41 kJ/mol (shift reaction)

(B) $CO_2 + 3\ H_2 \leftrightarrow CH_3OH + H_2O$ - 49 kJ/mol (exothermic)

Processes that directly link methanol synthesis to other processes are also being researched. At the Centre for Solar Energy and Hydrogen Research in Stuttgart, for instance, an integrated process has been developed that can be used to absorb CO_2 from the air, as well as to create methanol via a modified form of electrolysis with subsequent synthesis (Specht and Bandi 2007).

Detailed investigations are required to assess the overall efficiencies, and hence the CO_2 emissions, of such process variants in the current climate. It must also be considered whether there is enough "climate-friendly hydrogen," which would be required to support the process in the future. This is also needed elsewhere, so it is uncertain whether there would be sufficient availability for it to satisfy all demands.

4.2 Biological processes of CO_2 capture and use

There are already a number of ideas for using biological processes to capture CO_2 or to absorb CO_2 from the atmosphere. Here, we must differentiate between onshore and offshore options for use. In addition, research is also being carried out into processes to microbiologically transform CO_2 into CH_4 (methane).

Microalgae: Microalgae can provide over ten times as much biomass yield as higher land plants. Essentially, algae are able to absorb CO_2 from flue gases fed to them. The flue gases may have CO_2 contents of up to approximately 20 per cent. If microalgae were used in a bioreactor, CO_2-depleted flue gases would be emitted. The biomass created in the process would have to be separated by centrifugation, for instance, and further utilised (for example, to produce biogas, biodiesel, bioethanol or biohydrogen). There are around eight million species of microalgae, and so far only a handful have been used for this process.

Plants of this type would probably be used for smaller CO_2 sources if large areas or volumes are available for such bioreactors. Sunlight is required as the source of energy. This process is not yet ready for transferral to the large scale. A further yield increase is possible from a technical perspective by improving the design of the reactor and optimising the light input, e.g. by micro-structured plane light conductors (Ausfelder and Bazzanella 2008).

Microalgae cannot be used in the open air. They require a closed system or basin that ensures they are covered by water and mixed sufficiently. The net energy yield and amount of space required are the critical factors for evaluating the expediency of the process. To this end, the City of Hamburg launched the research project "Technologies to tap the resource microalgae" (TERM). A pilot plant for the absorption of CO_2 by algae was put into operation in mid 2008 (Bensmann 2008). The following sample calculation highlights the problem of the space required: according to Kerner's process, applied in Hamburg, a 21,500 hectare area of algae would be required for a modern 1,100 MW hard coal-fired power plant with a CO_2 emission of 5.4 million tonnes of CO_2/a.

RWE is also carrying out research into the possibility of microalgae binding CO_2. In the vicinity of the power plant in Bergheim-Niederaußem, flue gases from the plant are conveyed into an algae production plant to convert the CO_2 they contain into algal biomass. The aim is to investigate whether the algal biomass produced can be reused to make building materials or fuels. Up to 6,000 kg of algae (dry matter) can be produced annually by this plant, binding around 12,000 kg of CO_2 in the process (Beck 2008).

Enzyme development: The enzyme ribulose bisphosphate carboxylase/oxygenase (Rubisco) is ultimately responsible for plant systems absorbing CO_2 from the air. Efforts to genetically modify this enzyme could cause plant systems to store CO_2 more rapidly or efficiently. This initially applies to the growth period. Although CO_2 is produced again if the plant is later used as a bioenergy source, the energy yielded from it can be classified as CO_2-free, because the

CO_2 is removed from the air again in the next cycle. With this process, a net reduction effect can be realised in the timeframe if the biomass yielded is combusted on a large scale and the CO_2 produced is captured and stored. As it is in its early stages of development, commercial use of this process is not expected in the short term. One inhibiting factor, which could be important for public acceptance, is the use of genetically modified plants.

Microbiological transformation (methane production): Basic research is being carried out into the microbiological transformation of CO_2 into CH_4. This research is supported by programmes such as "Geotechnologies" (see Section 2.1.1).

Afforestation: The CO_2 reductions achievable through afforestation, or the prevention of deforestation, are identified as potential climate protection options in various investigations. Due to the limited space potential for this option to have a significant impact, it is generally restricted to areas outside Germany. Additionally, this process involves areas where there are competing demands on land use, and would only be effective in the long term. When applied to the large forested areas of the world, the discussion is much more complex because the interests of the groups involved are considerably more varied. Furthermore, ecological and social implications must also be considered.

Another option is to afforest or recultivate semi-arid areas where there had been low concentrations of biomass. An obstacle here, however, would be the large quantity of fresh water required and the competing demands for the water, which is also required for drinking or irrigating agricultural areas. A highly efficient irrigation system and measures to enhance the water storage capacity and to prevent soil erosion would be essential for the afforestation of semi-arid areas (GDCh 2003).

Induction of iron blooms: CO_2 can essentially also be bound by artificial algal blooms in the ocean. Iron fertilisation is required for this. In particular in the southern ocean areas, which have a shortage of iron compounds, an induction of iron blooms could cause the whole ocean system to absorb more CO_2. Various issues must be investigated here, such as the efficiency of the method and its potential ecological consequences, in particular its effect on marine ecosystems. The London Convention's scientific advisory body, amongst others, has highlighted the negative ecological impact of this method.

In collaboration with German and Indian scientists, an experiment (LOHAFEX) was carried out in the Atlantic at the beginning of 2009. However, no satisfactory results were obtained. Following the blooms created by iron fertilisation, the algae were consumed by copepods before they could settle on the seabed, as expected. The carbon therefore remained "bound" inside the copepods just beneath the surface of the water and was released again relatively rapidly. In addition to the, as yet unknown, ecological impact, therefore, there also has to be a great deal of research into the residence period of the CO_2 "separated" in this way (AWI 2009).

4.3 Other processes and approaches

Carbonisation of biomass: Max Planck Institute (MPI) in Potsdam is pursuing a process, called hydrothermal carbonisation (HTC), in which plant systems are effectively artificially carbonised by the addition of chemical substances at elevated temperature and pressure. The coal fraction can then be extracted from the biomass and reduced to a small volume.

The idea is that the coal produced can be used to enhance the soil or is added to the known industrial recycling states of lignite. Under the slogan “Magic Coal from a pressure cooker,” initial conversions have been successful within the laboratory. Although a total evaluation of the process has yet to be made, the subject of biocoal is also being researched at other universities and institutes, such as TU Berlin, Potsdam Institute for Climate Impact Research and Institute of Sugar Beet Research in Göttingen.

Storage of trees: The Institute of Biochemistry of the University of Greifswald proposes storing trees under anaerobic conditions (under oxygen exclusion) in mines, thus retaining the CO_2 underground for hundreds of years (Scholz and Hasse 2008). So far there has been no evaluation of whether the technical space and raw material potential is, or could be, available as a carbon sink in a significant form, and what socio-economic consequences may arise from it.

New catalysis: Many research projects in the field of chemical processes concentrate on the development of novel catalysts that can be used to cleave CO_2 in CO, or for conversion into a hydrocarbon. However, no large-scale feasible innovations have yet been identified.

New materials: Under the leadership of Gerard Ferey, Institut Lavoisier of the Université de Versailles Saint Quentin-en-Yvelines, French scientists have succeeded in developing a nano-powder that can be used to capture CO_2, amongst other things. A cubic metre of the substance MIL-101 (organometallic crystals) has been able to capture 400 m^3 of CO_2 in the pores of this nano-powder at a temperature of 25°C. According to Ferey, the powder could be used to filter out CO_2 from exhaust gas emissions. It is not yet known, however, what to do with the “CO_2 saturated” powder (Winter 2008).

Absorption to minerals: In natural weathering processes, CO_2 is bound to magnesium silicate. The atmospheric CO_2 is bound long-term for geological ages. This natural reaction is exothermic and spontaneous. When installed into the crystal lattice, therefore, energy is released over a period of between several hundred and one thousand years. To become technically applicable, this process must be greatly accelerated. Minerals found in large quantities throughout the world, such as olivine, wollastonite and serpentine, are used as the base material. These minerals are then mechanically comminuted and treated thermally. During an aqueous conversion, metals are dissolved out of the crystal lattice and converted into solution with the carbonate ions. The products and silicates then settle out of this solution. The thermal and mechanical pre-treatment, however, requires considerable energy expenditure. In addition, enormous quantities of reaction products accumulate (0.66 tonnes of quartz and 1.92 tonnes of magnesium carbonate per tonne of CO_2), which need to be transported (Ausfelder and Bazzanzella 2008).

5 Driving forces and attitudes of relevant stakeholders

In addition to purely technical factors, the development of CCS technologies is also dependent on so-called "driving forces", different aspects of which may have an influential and accelerating effect. These driving forces mainly include global climate protection, national supply and energy security, the development of technological potential for innovation and export opportunities, plant construction firms and other economic incentives (as already explained in detail in the RECCS study). Above all, such drivers give impetus to the development of CCS technologies in the long term, which is why their impact on the development of CCS technologies has not changed significantly over the past two years.

In contrast, the attitudes of interested parties towards CO_2 capture and storage over the last three years has become much more informed and differentiated. One indication of this is given when following the debate on the perspectives and potential of CCS technologies, which has steadily intensified and widened since the beginning of the 21st century. Not only are numerous experts from science and industry and politicians involved in the debate, now an increasing number of stakeholders from other social areas are also participating in the public exchange of opinions on the future of this technology. The following section provides an overview of the current discussion on CO_2 capture and storage. Anxious about existing and future projects and plans (such as exploration procedures and seismic measurements), the "concerned stakeholders" are increasingly engaging in this public debate, particularly those who live in the municipalities or federal states where potential storage site formations are located. The following illustration is based on a qualitative analysis of written position papers and comments by different stakeholders. The role of each type of stakeholder is described below. They are organised into categories, namely non-governmental organisations (NGOs), churches, political players, advisory committees and institutions, and scientists.

5.1 Non-governmental organisations

A large number of NGOs from a variety of social areas are now dealing with the subject of CCS. At the beginning of 2007, NGOs were mainly focusing on climate and environmental protection, and were expressing their views through the media. At that time, the debate about CCS was chiefly otherwise the domain of experts and specialists. Since then, just three years later, numerous other NGOs are among those institutions that have been partially responsible for raising awareness about CCS. Commercial and grassroots organisations deserve special mention here. These institutions and their respective stances and comments on CCS are presented below.

Climate and environmental protection organisations

We will first describe some of the climate and environmental protection NGOs operating nationwide. The current positions of the following NGOs were analysed in this context: Friends of the Earth Germany (BUND), Greenpeace, Germanwatch, German Environmental Aid (DUH), Nature and Biodiversity Conservation Union (NABU), World Wide Fund for Nature (WWF) and Robin Wood. All of these NGOs have already established their positions on CCS

CCS in publicly available papers. Their attitudes towards CCS range from being clearly in favour of it to its definite rejection.

The *WWF* and *Germanwatch* are among the clear proponents of CCS technologies, advocating its rapid development and market launch. Both NGOs envisage the application of CCS in biomass power plants and in the industrial sector, since so-called "net sinks" could be achieved and unavoidable process emissions stored (WWF 2009:2; Germanwatch 2009:2). They also call for a compulsory introduction of CCS technologies for combustors that emit over 350 grams of CO_2/kWh_{el}. The precondition, however, is that unresolved technical, legal and ecological issues should be resolved (WWF 2009:4; Germanwatch 2009:4).

NABU is one of the more cautious proponents of CCS. NABU's statement clearly suggests that CCS should primarily be further developed as an international climate protection option, as rapidly growing national economies such as India and China will continue to adhere to their coal-based power generation (NABU 2009:1). *NABU* also wants a minimum level of efficiency to be set for new fossil fuel-fired power plants.

DUH is neither a clear proponent nor opponent of CCS. Instead, this organisation seeks to prevent the construction of new coal-fired power plants through public lobbying. In their statement, they clearly express doubts about the large-scale applicability and economic feasibility of CCS technologies. From its criticism: *"Not even a 'capture ready' should become statutory in Germany,"* our understanding is, however, that they at least accept the use of CCS in future for all planned coal-fired power plants and for those under construction (DUH 2009:10).

In contrast, *BUND*, *Greenpeace* and *Robin Wood* oppose the use of CCS technologies. According to *BUND,* it is too late to implement this technology because, realistically, the implementation of CCS can only be assured from sometime between 2020 and 2025 (Jansen 2009:2). They argue that giving financial support to an uncertain technology such as CCS could block other future-oriented investments. According to *BUND*, the CO_2 pollution expected from emerging industrial nations (such as China) and the bridging function that some attribute to CCS are not adequate arguments for justifying this technology either. In addition, it remains uncertain whether power stations currently under construction will ever be retrofitted. *BUND* points out that sustainable clean forms of energy that could replace the fossil fuel coal can already be used today. In conclusion, *BUND* consistently backs energy efficiency and renewable energies.

With their climate protection scenario "Plan B 2050" (Barzantny et al. 2009:126) *Greenpeace*, too, takes an unequivocal stand against CCS in the power plant sector. CCS is not needed as a bridging technology, they say, and the expansion of coal-fired power plants generally undermines the goals of climate protection. In view of possible competing uses for the deployment of underground storage formations, *Greenpeace* supports making geothermal projects a priority and calls for this to be formally recognised in the legislation (Barzantny et al. 2009:75). *Greenpeace* does see potential for applying CCS in the industrial sector, and in combination with biomass. The organisation argues that the latter option is especially relevant in highly ambitious CO_2 reduction scenarios, which require negative net emissions worldwide in the second half of this century.

Robin Wood categorically rejects the construction of new lignite and hard coal-fired power plants and, as a consequence, the use of CCS technologies. The organisation calls instead for a radical change in energy policy. Moreover, it believes that CCS technologies will be applied too late to achieve the envisaged climate protection targets for 2020, since testing and development work still has to be done.

Compared with 2007, the opinions and positions of the various climate and environmental protection NGOs are now much more differentiated and substantiated. There are also a number of areas, however, where many NGOs reach a consensus. These areas can be seen in the aforementioned position papers and statements presented to the German government by many NGOs in May 2009 to help draft a bill on the regulation of CCS. In summary, these areas of agreement are:

- no priority of CO_2 storage sites over alternative forms of use of energy production, i.e. no exclusion of competitive uses,
- further research and development into CCS technologies using demonstration projects; transfer of research results into a future CCS law,
- assignment of more responsibility, post-closure obligation and liability to the operators according to the polluter pays principle, and
- creation of an underground development plan.

In conclusion, taking an overview of these groups, it emerges that there is no definite trend of being either opposed to or in favour of CCS technologies among the vast majority of the environmental and climate protection organisations in Germany.

Industry associations

The *Bundesverband der Deutschen Industrie e.V.* (*BDI*) sees in CCS technologies an important technological option for developing the climate-friendly use of lignite and hard coal. For this reason, they believe that this technology has the potential to contribute to energy supply security and to reducing Germany's dependence on raw materials, such as gas and oil. The *BDI* believes that CCS could herald an opportunity for economic players to take on a key role in a global future market (BDI 2009:1). The *BDI* believes a German CCS law should be heavily based on the EU Directive, and criticises that some parts of the current draft law extend significantly beyond the requirements of the European CCS Directive (for example, in the areas of liability regulations and financial security). They argue that such regulations would unnecessarily make the technology more expensive, and place German enterprises at a disadvantage compared with Member States that adopt the EU regulation without amendments or additions (BDI 2009:2). According to this Association, a future-oriented legal framework is required as soon as possible to ensure the rapid development of this technology and, in particular, to determine a liability ceiling (BDI 2009:3).

The *Wirtschaftsvereinigung Stahl* asserts that it will be impossible to implement CCS technologies prior to 2020. The steel industry is currently engaging in long-term research activities into new process technologies that could achieve considerable greenhouse gas reductions in future. The *Wirtschaftsvereinigung Stahl*, however, stresses that the economic efficiency and public acceptance of CCS technologies are, as yet, unknown territory. They believe that the way forward is framework legislation, that will enable the industry to carry out

demonstration projects in the future. To this end, discrimination-free access to carbon dioxide supply networks and carbon dioxide storage sites are required, in addition to non-excessive requirements with regard to the purity of carbon dioxide gases, investment incentives and a clear legal framework that does not impede the development of a transport and storage site infrastructure too greatly (Wirtschaftsvereinigung Stahl 2009:1).

According to the *Bundesverband der Energie- und Wasserwirtschaft e.V.* (*BDEW*), CCS signifies a commitment to coal and is, therefore, a future-focused, positive technology. In principle, they consider CCS technologies to be a possibility for utility companies to reconcile the requirements of global climate protection with the guarantee of ensuring the necessary energy supply security. According to them, this is also significant in that it will contribute to attaining energy policy commitment to continue to use coal as an energy source. The *BDEW* therefore also welcomes the draft law for the regulation of CCS by the German government, and calls for the law to be passed as soon as possible. This Association advocates having the EU CCS Directive translated and applied intact into national law. They consider it important to avoid unfair competition and to support German businesses that are introducing technical innovations for climate protection. They only support the German CCS law to a limited extent because of it having tighter controls than the EU CCS Directive. Their reservations are centred around the provision of financial security and the post-closure obligations (BDEW 2009:3). They consider the regulations on ownership structures at and around suitable CO_2 storage sites to be insufficient, and believe they will probably lead to considerable delays in CCS projects.

The *German Lignite Industry Association* (*DEBRIV*) is in favour of CCS technologies. They believe that CCS would give many countries the chance to develop and establish social justice. According to the German lignite industry, the draft law for CO_2 capture and storage presented by the German government is a vital contribution to securing the safe, climate-friendly supply of energy to Germany in future. *DEBRIV* considers it unjustifiable to delay or prevent the implementation of the bill. The draft law, they say, creates an important basis for establishing a transportation system and for developing and operating underground storage sites for captured carbon dioxide. They consider it suitable for establishing the foundations for future planning and investment security for enterprises. Coal will remain a vital element in the energy mix worldwide for the foreseeable future, and would be made sustainable by CCS technology. According to *DEBRIV,* other industries, such as the chemical or petrochemical industry, should also be given the opportunity to reduce their greenhouse gas emissions in this way with the assistance of new technologies (Maaßen 2009: 4).

The *Geothermische Vereinigung – Bundesverband Geothermie e.V.* believes there is a keen competitive relationship between CCS and geothermal projects. This is because the storage of CO_2 is in competition with the use of geothermal energy and the storage of compressed air. This could particularly affect areas in the northern region of Germany. The Association calls for a future CCS regulation that would deny a survey permit for CCS projects if a permit based on mining law was already in existence for the same area for the use of geothermal energy. The geothermal association suggests granting the competent (mining) authorities discretionary powers so that the relative advantages and disadvantages of the various uses of underground sites can be evaluated on a case by case basis, and that sufficient space be

ring-fenced for the future use of geothermal energy (Gaßner 2009:2, Bundesverband Geothermie 2009). The *European Geothermal Energy Council (EGEC)*, based in Brussels, goes one step further, calling for a clear priority for the use of geothermal projects over the storage of CO_2, since CCS is primarily only a bridging technology (EGEC 2009:2).

Trade unions

The *Confederation of German Trade Unions* (*DGB*) voices its concern that CCS is only one of many climate protection options and possibilities for securing energy supplies (DGB 2009:2). They argue that CCS technologies have not yet been sufficiently investigated with regard to their economic efficiency, technical feasibility and harmlessness to human health, nature and the environment. For this reason, the *DGB* insists on the implementation of demonstration projects in order to prove the suitability of CCS for reducing carbon dioxide emissions. If this is proved, all retrofittable power plants should preferably be equipped with CCS technologies. In this case, the *DGB* says, the intended CCS law should be updated according to the latest scientific and technical developments. This should be no later than when CCS technology is made obligatory for all new power plants. The law must guarantee a legal basis for the permanent storage of carbon dioxide in underground geological formations (DGB 2009:3).

The *Mining, Chemistry and Energy Industrial Union* (*IG BCE*) clearly advocates the further use of coal as an energy source. It supports the exploration and realisation of CCS technologies, yet warns against unnecessarily premature regulatory provisions. They argue that a statutory obligation to retrofit all new power stations with CCS technologies could jeopardise current modernisation work and the construction of hard coal- and lignite-fired power plants with higher levels of efficiency. Above all, CCS must be developed by 2020. To achieve this, according to *IG BCE*, framework conditions for pipelines and CO_2 storage sites must be created now (IG BCE 2008:7).

In summary, it becomes evident that relevant industry associations and trade unions (with the exception of national and international geothermal associations) mainly have a positive attitude towards the further exploration and implementation of CCS technologies. However, they do not expect this technology to be applied before 2020. They point out that economic and technical feasibility has not yet been sufficiently analysed. Contrary to the positions of most environmental organisations, the associations want a CCS law to be passed as soon as possible, which should be based largely on the EU CCS Directive. They stress that there should not be further regulatory intervention for financial security and post-closure obligations, at the expense of companies.

5.2 Churches

Representatives of different religious groups are now also becoming engaged in the public debate on CCS. Unsurprisingly, certain stances have become visible in the church districts where CCS activities are expected, as power stations already exist there, or they are potential storage locations.

The *North Frisia church district*, for example, takes a clear stance against CCS, in the form of opposing the *RWE DEA* exploration project (Kirchenkreis Nordfriesland 2009). The synod of *North Frisia church district* advocates a sustainable lifestyle that treats natural resources with

care and respect, and that does not jeopardise the lives of future generations. Members of the church therefore oppose energy projects with repercussions that are destined to last centuries or even millennia. Since the risks of CCS technologies are as yet unknown, concerns and fears among the population are necessarily greater, they claim. The church district calls on its federal state government and the German government to abandon the intended CCS law. They also appeal to utility companies to promote energy supply solely on the basis of renewable sources. In addition, they refer to possible conflicts of use, since other options for using deep geothermal energy or the storage of compressed air or hydrogen for wind energy purposes would be suited to this region. Last but not least, public commitment is mentioned. In recent years, this has been a major contributory factor in sustainable energy management (for example, public investment in citizens' wind farms *(Bürgerwindparks)* and the initiation of the *Aktivregion Nordfriesland Nord)*. Against the backdrop of these efforts, the citizens of North Frisia perceive that their dedication would be profoundly challenged if they have to bear the future consequences of an energy management that is no longer sustainable.

The committee of *Jülich Mitwelt* church district takes a slightly different stance. Representatives of the committee express their concern that the construction of new power stations in this region would lead to more open-cast mines being developed. They therefore urge the federal state government of North Rhine-Westphalia only to grant permission for new power plants if it does not involve the creation of new open-cast mines. Only then, they say, can the further "exploitation" of homelands and the resettlement of 9,000 to 12,000 more people in the open-cast mining regions be avoided. The representatives also voice their concern that the capture, transport and storage of CO_2 are very expensive and, from a technical point of view, harbour considerable risks. Other negative aspects of CCS technologies, they argue, include a reduction in power plant capacity, the fact that a technical solution may not happen before 2020, and that utility companies would request that the state contribute to costs. In conclusion, the church district considers a further use of lignite beyond the approved periods to be misguided as a suitable approach for energy supply in the future, since this would prevent the rapid and more comprehensive use of renewable energies.

On the basis of these two stances of church districts, it is clear that negative attitudes mainly emerge in the regions where the use of CCS could have a direct impact on the public and future generations.

5.3 Politics

5.3.1 Political parties

CDU

In a position paper on energy policy dated 16 July 2009, the German Christian Democratic Union (CDU) assigns a high priority to a "diversified and competition-oriented energy mix" (CDU/CSU 2009a) for future-proof energy policy. They assume that, even though there has been a strong growth in renewable energy sources, fossil fuels such as coal will be a central part of the energy mix for some time to come. Their use, however, should be as efficient and climate-friendly as possible. Against this backdrop, the CDU "expressly" supports the further development of CO_2 capture and storage, which "can make a vital contribution to the climate-friendly use of fossil fuels and climate protection worldwide," (CDU 2009a). This assessment

is mentioned again in the CDU manifesto for the 2009 Bundestag elections (CDU/CSU 2009b).

During the Bundestag debate on 6 May 2009, on a law for regulating underground CO_2 storage, speakers from the CDU/CSU parliamentary group emphasised that, in addition to the benefits of CCS technologies in terms of climate policy, there is also the opportunity to play a leading international role in the development and testing of this technology, creating a basis for technology exports. It was agreed that the draft for the CCS law should create reliable legal framework conditions for this process (Bundestag 2009).

In the course of further consultations on the draft law, however, it became obvious that there were diverse views on underground CO_2 storage within the CDU/CSU parliamentary group. In particular, members of parliament from constituencies where there will be site investigations for CO_2 storage expressed concern about public acceptance in the affected areas and about intervention in ownership structures. As a result of these objections, the law was defeated on 25 June 2009 and could not be passed, as had been planned, before the Bundestag elections in September 2009.

SPD

The German Social Democratic Party (SPD) is somewhat ambivalent when it comes to questions concerning the future use of coal in Germany. The SPD parliamentary group in the Bundestag, for example, is split between a coal-friendly and a more environmentally-oriented, coal-critical wing. For this reason, issues surrounding coal policy sometimes lead to controversial debate (Vallentin 2009). In 2007, the SPD's attitude towards CCS was outlined in the decision paper "Social democratic energy and climate policy for the 21st century". In this paper, it states that research activities into CCS technology for creating CO_2-free energy production are of central importance, and that Germany should expand its expertise in this field. From 2015, the first coal-fired power plant equipped with CCS technology in Germany is expected to be operational; CCS power plants are supposed to be standard by 2020. For this reason, the SPD supports any efforts to explore and test this technology (SPD 2007).

In their manifesto for the 2009 Bundestag elections, the SPD stated their position on CCS more precisely, including framework conditions for CO_2 storage. Primarily, the reuse of CO_2 is given priority over its underground storage. In the event of CO_2 storage, citizens affected should be involved in the approval process and companies must guarantee the permanence of the storage sites. The importance of CO_2 capture and storage for future energy supplies is also underscored in the SPD's manifesto by demanding that the revision clause for the German hard coal mining industry is applied "well before 2012", preventing the phasing out of the hard coal mining industry (SPD 2009). The SPD therefore gives coal a prominent position in the future German energy mix.

In the debate on the draft of a CCS law in the Bundestag on 6 May 2009, the SPD parliamentary group supported the draft law presented by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, led by the SPD at that time. Nonetheless, the SPD posed critical questions, such as ones associated with the necessary safety standards for storage, the assumption of the costs for the risks involved in CO_2 storage by the companies responsible and possible competition between CCS and other CO_2 reduction options, such as renewable energies or energy efficiency (Bundestag 2009).

FDP

In their Resolution of Intent on energy policy, dated 11 September 2008, the FDP (German Free Democratic Party) parliamentary group in the Bundestag underlined the crucial significance of a broad energy mix (FDP 2008). This would include renewables, nuclear power, coal, oil and gas, and is key to keeping Germany's dependence on energy imports as low as possible. The FDP assumes that coal will continue to play a leading role in German energy supply in the medium term, but that it should be used in a climate-friendly manner. Research into the development of CO_2 capture and storage is therefore given top priority in both the resolution adopted by the parliamentary group and in the policy statements on energy agreed on in 2006 at the FDP's federal party convention in Rostock (FDP 2006).

In their manifesto for the 2009 Bundestag elections, the FDP confirmed this position and called for CCS technology to be promoted through pilot projects and for the rapid creation of a legal framework. New coal-fired power plants should only be given planning permission if their design allows retrofitting of a system for CO_2 capture. In addition to CO_2 storage, the FDP calls for research into the options for the use of CO_2 and its legal implementation (FDP 2009).

Although the FDP accompanied the debate on the bill presented by the former German government for a CCS law quite favourably, they pointed out potential competitive uses when constructing a pipeline system for CO_2 transport and storage. When laying transport corridors, ownership conflicts and competitive uses with geothermal energy and (in the case of saline aquifers) the use of groundwater should be avoided (Bundestag 2009).

Die Linke

The core element of the energy policy programme of Die Linke (The Left) is a massive expansion of renewable energies and a considerable increase in energy efficiency. In their manifesto for the 2009 Bundestag elections, the Party calls for an increase in the share of renewables in the electricity sector of at least 50% by 2020. At the same time, it supports the phasing out of nuclear energy and a medium-term withdrawal from generating electricity from coal. They also oppose the planning and construction of new coal-fired power plants. This also applies to coal-fired power plants equipped with CCS technology, which they call an "illusory solution" and therefore equally reject. (Die Linke 2009a)

Eva Bulling-Schröter, environmental policy spokeswoman of Die Linke parliamentary group in the Bundestag, acknowledges that CCS may indeed serve as a bridging technology if necessary, but there is a risk that some of the impetus for the transition to renewables may be lost if attentions are focused on CCS (Die Linke 2009b). In consultation responses to the draft of the CCS law in May 2009, Die Linke criticised that the law would lead to a premature commitment to a technological path that has not yet been sufficiently explored. In this context, the party referred, above all, to various storage risks (for example, leakages caused by old boreholes). For this reason, Die Linke shares the opinion of the German Advisory Council on the Environment that the draft law should be changed to a research act, as a "minimum requirement". Die Linke also criticised the formal structure of the law, claiming that important details, such as the structure of the storage sites, the composition of the gas stream or the approval procedures for CO_2 pipelines, would have to be agreed upon subsequently by provisions without any involvement by legislators. (Bundestag 2009)

Bündnis 90/Die Grünen

The main focus of the energy policy of Bündnis 90/Die Grünen (Alliance 90/The Greens) is on renewables and energy efficiency. Both of these components would contribute to a drastic reduction in the use of fossil fuels and would promote climate-friendly energy supply (Bündnis 90/Die Grünen 2009a). The attitude of Die Grünen towards CCS technology is described in a position paper by the parliamentary group, dated 3 March 2009. Although the paper does not completely rule out CCS as a technological option for reducing CO_2, it makes a detailed inspection of the disadvantages and uncertainties related to this technology. In the debate in the Bundestag on the CCS draft law, the spokeswoman of Die Grünen parliamentary group drew attention to the high level of investment expenditure required for introducing the technology and the uncertainties regarding planning approval procedures for extensive underground CO_2 storage sites and laying CO_2 pipelines over long distances (Bundestag 2009).

Due to these objections, Die Grünen advocate that CCS technology must be scrutinised according to strict legal framework conditions and that there should be large-scale testing. The legal framework must stipulate, amongst other things, that the operators of CCS plants shall be liable, based on the polluter pays principle, for monitoring the storage sites and any damage that may be incurred. In addition, the storage sites shall be explored with maximum transparency, and access to CO_2 transport systems and storage sites shall be regulated without discrimination. Alternative uses of underground storage sites, such as to generate geothermal energy or to store compressed air, must not be disadvantaged by CCS projects.

In addition to these legal issues, Die Grünen stress that the use of CCS must not impede the complete conversion of the energy system to renewables. And hence financial support for research into CCS technology should not be at the expense of renewable energies. They also demand a moratorium on the construction of new coal-fired power plants until CCS has become a technical reality (Bündnis 90/Die Grünen 2009b).

5.3.2 The German government

The former German government, comprising CDU/CSU and SPD (2005-2009), considered CCS technology to be a vital element of their energy and climate strategy. In a speech delivered on 24 June 2009, the Federal Chancellor Angela Merkel (CDU) stressed that CCS could make a major contribution to reducing CO_2 and that it was of central importance to the further use and spread of German coal technologies. Consequently, restrictive legal framework conditions should not impede the testing and implementation of CCS technology (Merkel 2009).

Within the Black-Red German government, it was debatable for a long time who was responsible for CCS technology. In the end, the responsibility for drafting the CCS bill was assigned to the Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU), whilst the Federal Ministry of Economics and Technology (BMWi) accompanied the work process. In the debate on the CCS law, the former Federal Minister for the Environment, Sigmar Gabriel, pointed out that CCS was necessary for combating climate change and could also contribute to energy supply security and defending Germany's leadership in technology in the power plant sector (Bundestag 2009). As well as the national relevance of

CCS, he stressed the technology's significance for developing and emerging countries, such as China and India, where energy consumption, mainly comprising domestic coal, is increasing rapidly. For this reason, the opportunity to use coal in an environmentally-friendly manner is important in integrating these countries into a post-Kyoto agreement, Gabriel explained.

With regard to controversial questions regarding the CCS draft law, Gabriel indicated that the problem of possible competing uses with geothermal projects or compressed air reservoirs should not be overestimated, since the geographic distribution and the geological depths of such projects did not usually coincide with the corresponding requirements of CCS storage sites. Concerning companies' responsibility for the safety of such storage sites, Gabriel recommended coupling operating permits for CO_2 storage sites to obliging operators to adapt plants to the latest scientific and technological standards (Bundestag 2009).

The BMWi considers the use of CCS technology to be a precondition for retaining a balanced energy mix in Germany, based to a great extent on domestic energy sources. Moreover, the Ministry believes it is crucial that German climate protection technologies are devised and tested promptly to enable them to be made available worldwide. With regard to the CCS draft law, the importance of the cooperation between federal and federal state authorities, as well as between business and the public, is stressed, so that they can share expertise and engender a high degree of security and acceptance (BMWi 2009a).

The new German government elected in September 2009, comprising CDU/CSU and FDP, supports the development and market launch of CCS in their coalition agreement. To this end, they announced that they would implement the EU CCS Directive "soon" and would promote public acceptance of the technology (CDU/CSU and FDP 2009). CDU/CSU and FDP also intend to commission the preparation of a "geothermal atlas" to examine competing uses with CCS and to expand research programmes on options for using CO_2.

5.3.3 Bundesrat and German federal states

In the CCS draft law, the German federal states play a central role, since they will be assigned important duties concerning the monitoring of storage sites and providing data to the Federal Institute for Geosciences and Natural Resources (BGR) for the analysis of storage site layers. This particularly applies to the northern federal states of Schleswig-Holstein and Lower Saxony, where most of the potential CO_2 storage sites are located. On 15 May 2009, the Bundesrat therefore gave a comprehensive statement on the German CCS draft law, criticising numerous technical, ecological and financial aspects of the bill and its stipulation of burden sharing between the federal and state governments.

With regard to the latter aspect, the following proposals for amendments are particularly relevant (Bundesrat 2009):

- the federal states should be given the opportunity to comment on the processing and evaluation of regional geological data by the BGR and the resulting conclusions by the BMWi,
- the federal states oppose the exemption from costs awarded to former operators of closed CO_2 storage sites, since this violates the precautionary principle. For this reason, they are calling on the German government to investigate options for introducing regula-

tory controls for the plant operators having to accept financial responsibility for any damage incurred, even after responsibilities have been transferred to the state,

- since potential CO_2 storage sites are situated in just a few German federal states, the Bundesrat states that the Federation should assume all risks associated with CO_2 storage to avoid this handful of states being unfairly burdened.

At federal state level, the CCS debate has also gained momentum. Here, the viewpoints vary between approval and rejection. In July 2009, the federal state parliament of Schleswig-Holstein argued unanimously in favour of stopping soil explorations conducted by RWE Dea in the districts of Schleswig-Flensburg, North Frisia and Eastern Holstein at the request of the CDU/SPD parliamentary groups. They consider the investigations into potential CO_2 storage to be unnecessary in view of the Federation's adjournment of the decision on the controversial CCS law. They also believe that the technology is not yet fully mature (Landtag Schleswig-Holstein 2009a). In September 2009, the parliamentary groups of the SPD, Bündnis 90/Die Grünen and the Southern-Schleswig Voters' Association (SSW) also called on the federal state government of Schleswig-Holstein to pursue the goal of prohibiting CO_2 storage via the Bundesrat (Landtag Schleswig-Holstein 2009b). Subsequently, the CDU and FDP tabled an amendment in which the federal state government is pledged to ensure that, in the new national CCS law, the German federal states will be given independent rights to exclude the permanent underground storage of CO_2 from their territory. The federal state government should not be able to allow the underground storage of CO_2 against the will of the population (Landtag Schleswig-Holstein et al. 2009c). The CDU of Schleswig-Holstein, however, opposes a nationwide prohibition of CO_2 storage (Landtag Schleswig-Holstein 2009d).

In their coalition agreement, finalised on 17 October 2009, the newly elected federal state government of Schleswig-Holstein, comprising the CDU and FDP, categorically rejects CCS technology, too. In compliance with the motion for amendment from the CDU and FDP state parliamentary groups, the coalition backed the inclusion of a right to veto in the CCS law so that affected federal states have the power to reject CO_2 storage projects in their territory (CDU Schleswig-Holstein and FDP Schleswig-Holstein 2009).

In the coal-producing federal states of Brandenburg and North Rhine-Westphalia, on the other hand, the majority approves of CCS. The Premier of Brandenburg emphasised in spring 2009 that it is crucial that a legal framework for CO_2 storage is established soon in order to maintain Brandenburg's dominant technical position in generating CO_2-low power from lignite (Staatskanzlei Brandenburg 2009). Against this backdrop, the former federal state government, comprising the SPD and CDU, also advocated the exploration of potential CO_2 storage sites in the Oder-Spree district. Both governing parties insist, however, that the process be carried out as transparently as possible, and with public participation, to achieve a high degree of public endorsement and acceptance (SPD-Landtagsfraktion Brandenburg 2009).

The federal state's stance towards CCS had to be realigned, however, after the federal state election in Brandenburg in September 2009, that resulted in the formation of a new federal state government, comprising the SPD and Die Linke. In contrast to the SPD, Die Linke in Brandenburg had argued for a medium-term withdrawal from generating power from lignite by "2040 at the latest" in their manifesto (Die Linke Brandenburg 2009) and also rejected CO_2 storage (TAZ 2009). As a result, the two issues became the subject of controversial de-

bate during coalition negotiations with the SPD. In the coalition agreement of the new federal state government, however, the coalition now supports the demonstration and testing of CCS technology. As from 2020, new lignite-fired power stations shall only be approved if CO_2 emissions are "drastically" reduced (SPD-Brandenburg and Die Linke Brandenburg 2009). With regard to the research and use of CO_2 storage sites in Brandenburg, the safety of the population is paramount. Regional, social and ecological conflicts shall be minimised by providing detailed information to the population and enhanced mediation by the state. Moreover, the challenge now was to coordinate the competing claims on the use of potential CO_2 storage sites, for example, for deep geothermal energy (SPD-Brandenburg and Die Linke Brandenburg 2009).

The federal state government of North Rhine-Westphalia (NRW) supports CCS and the creation of a corresponding legal framework, and attempts to reduce the public's reservations about the construction of coal-fired power plants or CO_2 pipelines through dialogue, and to promote technical exchange on CCS. One way in which this is being achieved is through the "Power Plant Technology Network NRW", organised by EnergyAgency.NRW, which has already held various symposia on this subject. At question time in the federal state parliament of NRW in June 2009, the use of CCS technology was approved by all parliamentary groups, with the exception of Die Grünen (Landtag NRW 2009). Christa Thoben, Federal State Minister for Economic Affairs and Energy, clearly favours CCS and also supports the CCS draft law. She has also supports RME's CCS project in Hürth near Cologne (MWME NRW 2009).

5.3.4 Local authorities

In 2010, the utility companies RWE, E.On and Vattenfall Europe started exploring possible CO_2 storage sites. RWE Dea is investigating potential storage sites in the districts of North Frisia and Schleswig-Flensburg in Schleswig-Holstein. E.On Gas Storage GmbH has applied for permission to Lower Saxony State Office for Mining, Energy and Geology (LBEG) to investigate possible CO_2 storage sites in the area of the River Weser. The application comprises 17 districts and urban districts in Lower Saxony and Bremen. Vattenfall Europe may investigate suitable storage site formations in East Brandenburg. The company has submitted the relevant applications for exploration to the Brandenburg State Office for Mining and Geology in Cottbus. The explorations focus on the East Brandenburg regions of Beeskow and Neutrebbin.

The exploration of geological formations in northern Germany, carried out in order to assess their suitability as potential CO_2 storage sites, has, however, provoked resistance in the regions concerned. Numerous municipal bodies have expressed their rejection of CCS technology in recent months. Some of these initiatives are listed below:

- *Rural district of Leer:* In a statement to the LBEG, the administration of the rural district in Lower Saxony emphasised its opposition to CO_2 storage, because too little is known about its possible consequential damage; it has not yet been sufficiently researched whether the underground storage of CO_2 can guarantee its permanent and safe disposal.
- *Insel- und Halligkonferenz:* This association opposes CCS, since the technology does not prevent the production of CO_2. Furthermore, gas would have to be transported long

distances to storage sites and the environmental impact of CO_2 storage has not yet been researched in sufficient depth. Due to the potential negative impact on nature and tourism, the body instead advocates the expansion of renewable energies (Neue Energie 2009a).

- *Gemeindetag Nordfriesland:* On behalf of the 126 municipalities belonging to the district association, the Gemeindetag spoke out in a resolution against a final CO_2 disposal site and exploration processes carried out by RWE Dea. In this resolution, the German government is urged not to pass the bill for a CCS law due to the possible risks involved in storage and the potential negative impact on the Wadden Sea. It opposes the federal state government of Schleswig-Holstein using the region as a "test area" for CCS (Der Inselbote 2009).
- *Schleswig County Council:* In a resolution in July 2009, the County Council rejected the German government's draft for a CCS law and the storage of CO_2 in the district of Schleswig. It calls on the German and federal state governments to ban any funding for research activities on CCS technology. In another resolution, they urge RWE Dea to refrain from carrying out the intended seismic measurements in their search for suitable CO_2 storage sites in the region (Schleswig-Holsteinscher Zeitungsverlag 2009a).
- *Kappeln Town Council:* At the request of Die Grünen parliamentary group, the Town Council passed a resolution against a CO_2 storage site planned by RWE in Schleswig-Holstein. They justify the rejection of CCS on the grounds of competing uses by alternative energy technologies, such as geothermal energy, and also the potential negative impact on tourism in the region and the high costs of the technology compared with other alternative options for generating energy (Schleswig-Holsteinscher Zeitungsverlag 2009b).
- *Beeskow (Oder-Spree) local representatives:* Seven mayors and directors from the region around Beeskow (Brandenburg) have published a joint statement in which they reject both CCS and the intended exploration of a potential storage site near Beeskow. The reasons they give are that the project is damaging to the region's good reputation and tourism, and that it is associated with too many uncertainties. According to plans by Vattenfall, CO_2 from the future demonstration power plant Jänschwalde will be liquefied and pumped through pipelines to storage sites in East Brandenburg from 2015 (Neue Energie 2009b).

In conclusion, it can be stated that the majority of parties represented in the Bundestag and the German government support the use of CCS. Die Linke is its most vehement opponent. Die Grünen demand a strict framework of rules and regulations for the use of this technology, and a clear priority for renewables. At federal state level, Schleswig-Holstein state government and all parties represented in the Schleswig-Holstein state parliament clearly oppose the storage of CO_2. This attitude is reinforced by the firm public rejection in potential storage site areas. Highly industrialised, coal-producing federal states, such as Brandenburg and NRW, on the other hand, are supporters of CCS. A two-level conflict is therefore emerging: at the first level, between federal states with a great CO_2 storage potential and the German government and, at the second level, between the "storage states" and all other federal states where coal still plays a vital role with regard to structural policy.

5.4 Advisory bodies and institutions

German Council for Sustainable Development

The German Council for Sustainable Development was convened by the German government in 2001 to contribute to the implementation of the German sustainability strategy and to identify significant problem areas concerning this subject. In recent years, this body, also called the "Sustainability Council", and, in particular, its Chairman Dr. Volker Hauff, has become an important advocate of CCS technology. In a resolution as early as in 2003, the Council described CCS technology as a precondition for the sustainable use of coal and, therefore, as a "necessary stage of development" (Rat für nachhaltige Entwicklung 2003).

This position was further specified in the ensuing years. In autumn 2008, the Council published a position paper on important issues concerning energy policy, in which CCS technology is classified as a central option for reducing CO_2, especially within the global context. Since Germany is a country with a long tradition of eminence in the field of energy technology, it has a global responsibility to develop and apply CCS technology. They therefore call a halt to the approval of any coal-fired power plants without CCS after 2015, and that all new fossil fuel-fired plants from 2010 must be retrofittable. For existing plants that emit more than the respective average of hard coal and lignite-fired power plants, proposals are being made to ensure they are retrofitted now, according to regulatory law (Rat für nachhaltige Entwicklung 2008).

During the debate on the CCS draft law by the German government in summer 2009, Hauff emphatically spoke out in favour of this technology being used and promoted, as it was not yet possible to secure Germany's energy supply on the basis of renewables alone in the decades to come. Hauff therefore backed the CCS law and also asked for a large-scale research initiative on CO_2 processing and for its application as a resource (Rat für nachhaltige Entwicklung 2009a). He called the concerns expressed by environmental associations about CCS technology "provincial" (Rat für nachhaltige Entwicklung 2009b). In December 2009, Michael Vassiliadis, Chairman of the Mining, Chemistry and Energy Industrial Union (IG BCE) and member of the Sustainability Council, requested that the German government promote CCS technology and work towards increasing public acceptance of this technology (Rat für nachhaltige Entwicklung 2009c).

German Advisory Council on the Environment (SRU)

The SRU was established by the German government in 1971, and was therefore one of the first institutions to provide scientific policy advice to Germany's environmental policy. The remit of the Council is to describe and assess the environmental situation and environmental policy in Germany and their development trends. Its role is to expose misguided eco-political developments so that they can be avoided or eliminated.

In a public hearing on the CCS law in the Bundestag on 25 May 2009, the SRU criticised the current draft of the law. Their statement focuses on uncertainties with regard to the scope of storage capacities and the ecological risks involved in CO_2 storage. In addition, the SRU refers to possible alternative uses for CO_2 storage sites, including deep geothermal energy, compressed air and natural gas storage, as well as the high costs of CCS.

The SRU rejects the draft law of the former German government, as so many uncertainties remain. For example, because of these uncertainties, the SRU believes that it would be inappropriate and premature to prescribe powers to issue statutory instruments regarding such important issues as financial security. This would allow decisions on vital issues to be made without the involvement of parliament.

Additionally, it claims the bill fails to ensure a "strategic and long-term assessment of the possible conflicts of interest," (SRU 2009a). Consequently, it would lead to a period of long-term political inflexibility, since the decision on the type of use for available storage sites signifies a significant "strategic turning point," (SRU 2009a). It also criticises that transferring responsibility for the storage sites after a period of 30 years means shifting the costs to the affected federal states in northern and eastern Germany, equating to an indirect subsidisation of CCS operators.

Due to the reservations outlined above, the SRU supports a research law that enables CCS to be tested in a limited number of demonstration plants. In this way, it wants to avoid making a sweeping decision on the application of this technology before the opportunities and risks have been investigated thoroughly. During the negotiations for the coalition agreement of the new German government, the SRU reaffirmed its previous position on CCS in a letter to the representatives of CDU/CSU and FDP in the negotiation groups for the economy, the environment and energy. The letter states that a new CCS law should make provision for a management concept for the storage areas. As far as the use of the storage sites is concerned, the SRU recommends giving priority to CO_2 captured from biomass-fired power plants and industrial processes, as well as to geothermal energy and energy storage over CO_2 capture from power stations (SRU 2009b).

Office of Technology Assessment at the German Bundestag (TAB)

The TAB was established at the German Bundestag in 1990 to create a knowledge base for research- and technology-related decisions. In November 2007, the Office published a progress report on the subject of CO_2 capture and storage. In addition to greenhouse gas reduction, the report also focuses on the gentle exploitation of finite resources, economic efficiency and social aspects (such as public acceptance, dealing with long-term risks) as essential criteria for the assessment of this technology. There remains a great deal of uncertainty regarding these points, which is why the TAB concludes that the current knowledge base is "nowhere near sufficient for a substantiated assessment of the technical and ecological feasibility of CCS nor can it appraise how this technology can contribute to achieving the goal of climate protection," (TAB 2007). It states that it is therefore necessary to close these gaps in the knowledge. The TAB mainly considers industrial companies to be responsible for research and development in the areas of CO_2 capture, CO_2 conditioning and CO_2 transportation. The main task of the state is to create reliable legal framework conditions for these activities and to carry out research into CO_2 storage.

In order to create such a legal framework, the TAB proposes a two-phase procedure. In the short term, an "interim solution" for assisting the implementation of upcoming CCS projects should be devised (TAB 2007). At the same time, they believe it essential to devise a comprehensive regulatory framework to follow this interim solution once CCS is available on a large scale.

As far as CO_2 storage is concerned, the TAB identifies considerable need for research into potential competitive uses (for example, natural gas storage or deep geothermal energy) in addition to issues about CO_2 interactions with underground rock and a precise determination of storage site capacity. At the same time, it stresses that technological research into CO_2 capture and storage must be supplemented by social and eco-scientific research. This is necessary, they say, to facilitate a solid assessment of the economic, ecological and social impacts of CCS technology. Furthermore, the TAB believes that a nationwide communication, information and participation strategy should be devised in order to encourage public acceptance.

German Federal Environment Agency (UBA)

The German Federal Environment Agency, founded in 1974, is Germany's central environmental authority. It offers the German government scientific support, and is responsible for enforcing environmental laws. In a position paper published in 2006, the UBA advocated a sustainable climate policy, primarily focusing on converting to renewable energies and enhanced energy efficiency. CCS, on the other hand, is classified as being an unsustainable technology, due to efficiency losses as a result of CO_2 capture and the finiteness of CO_2 storage site options. The UBA acknowledges, however, that the technology could be necessary as a transitional option if certain basic conditions can be guaranteed, such as a maximum leakage rate of 0.01 per cent per annum and the development of a sophisticated legal framework to ensure high standards in storage safety. (UBA 2006)

In May 2009, the UBA published an updated position paper on CCS technology. In this paper, it is also stressed that Germany would be able to achieve its climate protection goals through considerable energy savings and a consistent use of renewable energies, even without CCS. CCS is regarded merely as a transitional technology and should be adopted only if measures to increase energy efficiency and to promote the use of renewables are unsuccessful. In particular, the UBA highlights the technical uncertainties at all levels of the CCS process chain and possible conflicting interests with geothermal heat and electricity production. The Agency therefore advocates creating underground spatial planning to avoid individual conflicts with regard to the use of geological formations. (UBA 2009a)

German Advisory Council on Global Change (WBGU)

The WBGU was founded by the German government as an independent, scientific advisory body in 1992. Its principle tasks include analysing and evaluating global environment and development problems, as well as monitoring and assessing national policies for the achievement of sustainable development.

In 2006, the WBGU published a special report on the future of oceans, which explored the warming up and acidification of the oceans (WBGU 2006). In one chapter of the report, the possibilities of CO_2 storage in the ocean and below the ocean floor, as well as the potential, the costs, risks and legal implementation of these options, are explained and discussed. Due to the unpredictable impact on the ecosystem, the WBGU categorically rejects storage in the ocean, for example, by direct injection of the gas or its storage on the ocean floor. The Council recommends instituting a worldwide ban. The report also points out the futility of ocean storage of CO_2, as it would not reduce the long-term impact of CO_2 emissions, due to the permanent interaction between oceans and the atmosphere.

As for CO_2 storage below the ocean floor, the report reaches a more differentiated verdict because the risk of negative environmental impacts is considered to be lower. In view of the rapidly increasing demand for energy in developing and emerging countries, the WBGU considers this method of CO_2 storage to be a possible transition technology, complementing more sustainable CO_2 reduction strategies. The report points out, however, that the promotion of CCS technology by politicians and business should not result in renewable energies and energy efficiency being sidelined. Furthermore, it recommends regulating the use of the technology through a legal framework and restricting it to a limited period of time (for example, a few decades).

In summary, this analysis shows that that advisory committees to the German government mainly have a negative attitude towards CCS technology. SRU, TAB, WBGU and UBA highlight the major uncertainties associated with the use of the technology, in particular its storage, and warn against hasty strategic decisions being made. In addition, they believe the technology must not impede the development of renewable energies and the enhancement of energy efficiency. The UBA, in particular, classifies CCS as unsustainable within the definition of sustainable development. On the other hand, the German Council for Sustainable Development advocates taking a leading role in the development of CCS to facilitate the sustainable use of coal.

5.5 Science

Öko-Institut e.V.

In the public hearing at the Bundestag, the Öko-Institut declared CCS technology to be an "important CO_2 reduction option ... – not only globally, but by all means also for Germany," (Matthes et al. 2009). The potential fields of application are regarded as being not only the power plant sector, but also the avoidance of CO_2 from industrial sources, such as the steel industry, cement manufacturing and the chemical industry. The Institute emphasises that CCS should be classified as a "multi-use option", because it is essential for reducing industrial process emissions both nationally and internationally in order to achieve the 2°C target. In Germany, process emissions amount to 80 million, and 2.5 billion tonnes per annum worldwide (Energiewirtschaftliche Tagesfragen 2009). This is equivalent to a share of 9 per cent in Germany's total energy-induced CO_2 emissions. Globally, the share constitutes about 8 per cent (BMWi 2009b).

The Öko-Institut basically supports the creation of a long-term regulatory framework, including a revision clause introduced by the German government. The Institute, however, criticises many detailed aspects of the law. For example, the draft law does not include sufficient elements for investigating and solving long-term competitive uses, nor is there an instrument for devising a comprehensive CO_2 transport infrastructure. They insist that both of these issues must be taken into consideration in an amendment of the law in 2015. They also recommend ensuring sufficient timely information and public participation to avoid acceptance problems at the storage sites.

Other sections of the draft law, such as the transfer of responsibility for CO_2 storage sites to the federal states after 30 years and obligations to provide financial security, are viewed as

positive. In addition to national regulations, the Öko-Institut proposes devising programmes to initiate a transfer of knowledge with regard to CCS regulation (Öko-Institut 2009).

Potsdam Institute for Climate Impact Research (PIK)

Represented by Professor Hans-Joachim Schellnhuber, Director of the Institute, and his deputy Professor Ottmar Edenhofer, PIK has repeatedly referred to the use of CCS technology as a precondition for achieving the 2°C target. According to Edenhofer, an ambitious climate policy without CCS would require a rapid withdrawal of the use of coal. This would mean, however, that the abundant coal reserves of the world's largest CO_2 emitters, such as China, the USA and India, would be devalued and these countries would not participate in an international agreement on climate protection (TAZ 2009).

PIK further argues that CCS is not only significant in terms of coal use, but could also be applied in combination with biomass combustion. If CO_2 is emitted during the combustion of biomass, negative emissions would occur, as energy from plants can basically be used in an emission-neutral way, due to their ability to bind carbon. The application of biomass CCS systems, they explain, is especially necessary with regard to ambitious climate protection routes that require a greenhouse gas concentration of 400 ppm in the atmosphere to meet the 2°C target. PIK therefore requests the use of the limited resources to store CO_2 for biomass CCS processes, since this is the only way to achieve negative emissions (Edenhofer et al. 2009). The Institute also recommends introducing a scarcity price for the use of underground storage sites to ensure their maximum efficiency in terms of time and sectoral use. Edenhofer supports the creation of demonstration power stations to illustrate technical and economic feasibility, ecological effectiveness and, in particular, the social acceptance of the technology.

Forschungszentrum (FZ) Jülich

Under the umbrella of Forschungszentrum Jülich, various institutes are working on the topic of CCS. The subjects range from the development of new technologies for CO_2 capture and assessing the energy-efficiency and environmental impacts of the technology. In model calculations on energy and climate policy, FZ Jülich concludes that CCS technology may play an important role within a cost-optimal climate protection strategy for Germany. Assuming that CO_2 can be reduced by 40 per cent by 2030 compared with 1990 levels, cost savings will amount to € 20 billion between 2020 and 2030, thanks to the use of CCS (Martinsen et al. 2006). The scenario calculations assume that CCS will be marketable from a price of € 30 per tonne of avoided CO_2.

Institute for Futures Studies and Technology Assessment (IZT)

IZT is a non-profit research institute that devises technology assessment scenarios used to shape recommendations for politicians, business and civil society. Professor Rolf Kreibich, Director of the Institute, clearly spoke out against the use of CCS technology at an awareness raising event on CCS in Schleswig-Holstein. He argued that it leads to a significant increase in demand for primary energy for fossil fuel-fired power plants and also generates high costs, whilst the benefits of achievable capture rates and levels of efficiency are still largely unknown. Furthermore, unpredictable risks in the storage areas were involved, since large-scale CO_2 storage was associated with "totally unknown impacts, impermeabilities, investigations, monitoring, possible accidents, environmental impacts and health hazards."

Ultimately, CCS would prolong the use of central, fossil fuel-fired large power plants and drain funds required for promoting renewable energies (IZT et al. 2009).

In summary, it can be said that German research institutions take an ambivalent stance towards CCS technology. PIK and Öko-Institut regard CCS as a necessary climate protection option that should be employed in certain sectors (such as heavy industry) or countries (such as China and India) where otherwise it would be difficult to achieve reductions in CO_2 and the associated structural change. FZ Jülich considers CCS to be an important option for Germany, too, whereas this technology is generally rejected by IZT.

5.6 Summary assessment of the attitudes of relevant stakeholders

In recent years, the number of players involved in the public debate on CCS has steadily grown. In 2007, mainly utility companies and environmental organisations were involved in the public debate, and it was given only brief coverage in the media. Today, the issue ignites diverse debate across a whole spectrum of social, economic and political groups.

The topics on CCS technologies now being debated are much more focused. While in 2007 discussions mainly addressed the technical and economic feasibility of the technology, there is now much broader and more open exchange on the topic, involving advanced aspects, such as potential competitive usages with other technologies and liability issues. Reports on CCS are no longer restricted to the context of coal-fired power plant technologies. It is noticeable that greater attention is now being paid to industrial applications of the technology as an option to reduce process emissions. The technology is also being mentioned more frequently in the context of biomass use. In Germany, the focus is primarily on the technical advancement of CCS technologies; most stakeholders believe that these technologies are best implemented and applied in the aspiring industrial nations that have considerable deposits of coal (such as China and India).

The growing expertise about CCS technologies goes hand in hand with stakeholders adopting increasingly strong positions. One specific aspect of this debate, however, remains constant: the opinions and attitudes on the subject of CCS are strongly divided between its opponents and supporters, sometimes even within the same groups (for instance, environmental NGOs and science). Fig. 5-1 summarises where stakeholders are positioned on a continuum between endorsement and rejection, based on their formal statements and opinions.[11]

[11] The individual stakeholders were classified by a purely qualitative analysis. Fundamental statements on CCS technologies by the stakeholders were decisive for their classification.

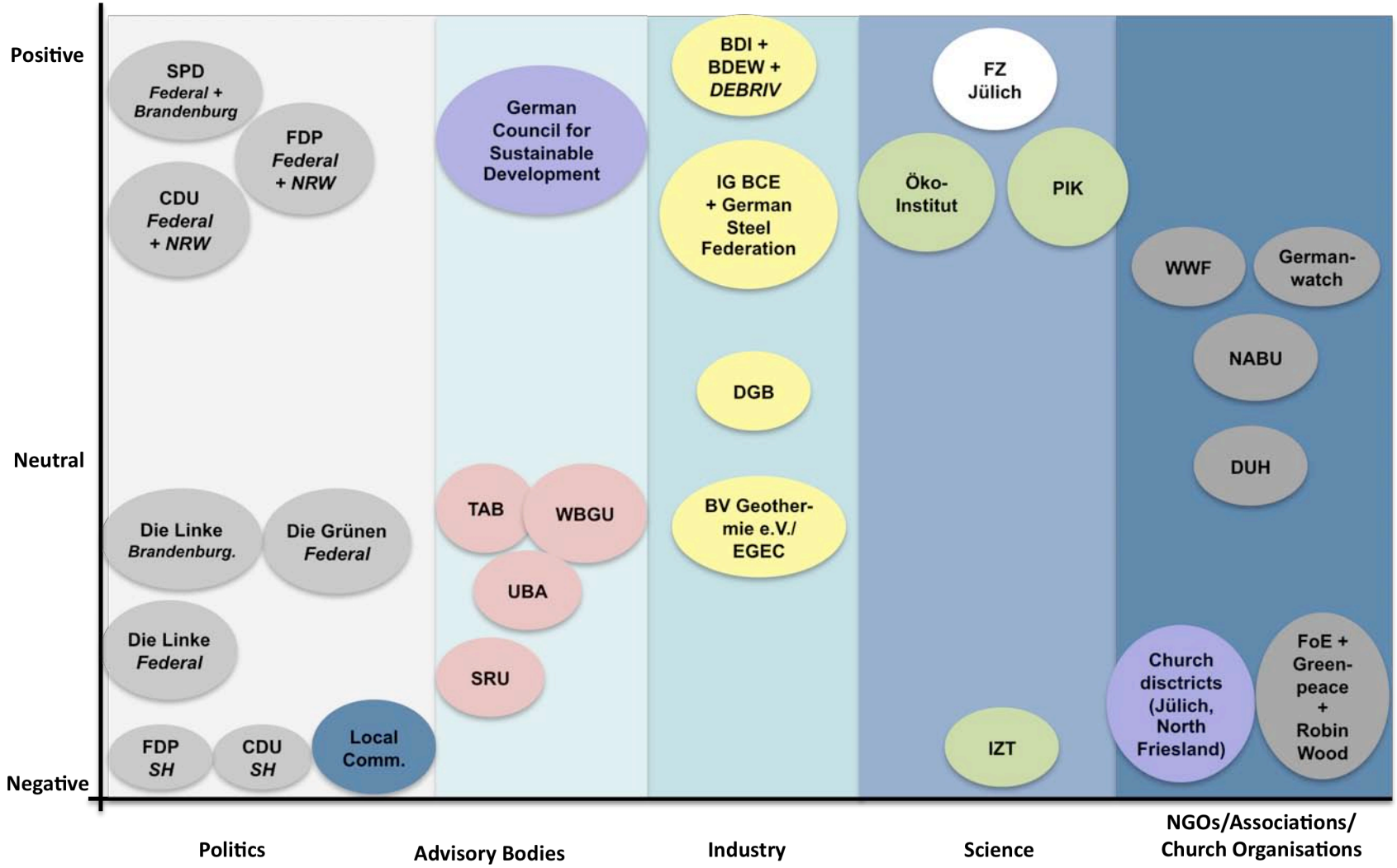


Fig. 5-1 Overview of attitudes of relevant stakeholders from the area of CCS

Source: Authors' design

6 Legal aspects of introducing CCS to power plant technology

The political, socio-economic and legal aspects of CCS have been at the forefront of national and international discussions since the publication of the IPCC Special Report on Carbon Capture and Storage in 2005. Prior to this, much of the debate had been focused on the engineering, economic, geological and geotechnical aspects of CCS. Following the publication of this Report, it soon became clear that the existing legal framework was inadequate for:

- establishing the legal and investment security for project organisers essential for investments in R&D and
- accurately assessing the hazards and risks involved, particularly in the permanent storage of CO_2, in the final stage of the CCS process. This has to be assessed alongside a sufficient storage duration required to have an impact on climate.

This appreciation of these shortcomings in the legal framework did not apply to German law alone (Dietrich 2007, Grünwald 2007), but also to the existing legal frameworks of other EU Member States, as well as European law and international agreements (IEA 2005, Hendriks et al. 2005).

Rapid changes were made to European law to support the political targets for dramatic reductions in CO_2 emissions to mitigate global climate change. A viable legal framework for the CCS process to be able to make an impact on climate and the environment had to be devised. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending other legal acts (for short: CCS Directive 2009/31/EC) came into effect on 25 June 2009. Now the same standards apply throughout the Community with regard to the requirements governing CCS technology. For the CO_2 capture and transport processes, the Directive partially relies on existing provisions. However, an entirely new legal order has been created for the final step: the permanent storage of CO_2. Consequently, legal developments in the Member States appear to be inevitable where they decide in favour of regulating and deploying CCS technology in their own sovereign territories.

The central legal aspects regarding the use of CCS technology are classified as follows:

- legal framework for CCS technology at the level of European law
- legal framework of international agreements
- developments outside the EU using the example of the U.S. State of Wyoming and the Australian State of Victoria
- implementation in other EU Member States, using the example of the Netherlands and Poland
- legal framework for CCS technology in Germany (merely a summary of the German part of the report).

The scope of this analysis is not to cover all conceivable technical processes and options for CCS use. Instead, the report focuses on the use of CCS technology in fossil fuel-fired power plants.

6.1 Legal framework for CCS technology at the level of European law

6.1.1 Developments

The second phase of the European Climate Change Programme (ECCP II) was launched in February 2005 by the Communication from the Commission entitled *"Winning the Battle Against Global Climate Change"*.[12] This was to form the basis for future EU climate policy. At the same time, a working group to investigate *"Carbon Capture and Geological Storage (CCS)"* was established.[13] Besides assessing its potential, this Working Group III was to develop economic aspects and the risks involved in CCS technology and, in particular, the need for regulatory action. It was also given the task of describing and exploring the core elements of a suitable legal framework for the development of the environmentally safe use of CCS technology. In the Final Report of Working Group III, presented in June 2006, it was concluded that there was a substantial need for judicial regulation. In addition, the Commission was requested to change the role of CCS through the authority of European law, in particular with regard to water and waste law, to create a clear political and legal framework for the use of CCS and to remove existing legal obstacles (ECP II 2006).

In the communication *"Limiting Global Climate Change to 2 Degrees Celsius – The way ahead for 2020 and beyond"* of 10 January 2007, the EU Commission stressed that CCS technology should be viewed as a future option to enable the continued use of fossil fuels.[14] In its communication *"Sustainable power generation from fossil fuels: aiming for near-zero emissions from coal after 2020"* released on the same day, it emphasised that a legal and political framework for CCS should be created in the EU. In addition, obstacles within existing laws should be removed to enable CCS to be used in an environmentally friendly, safe and reliable manner, and to set suitable incentives for the use of CCS.[15]

In compliance with the request by the European Council of March 2007[16] to create the necessary legal framework, the EU Commission presented its much-publicised draft of a Climate and Energy Package on 23 January 2008 (see also Fig. 2-2). A main element of the legislative package was the Commission's proposal for a directive on the geological storage of carbon dioxide and for amending Council Directives 85/337/EEC and Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No. 1013/2006.[17] After consultations, hearings and obtaining the necessary position statements, the European

12 COM(2005)0035.

13 Accepted Final Report of Working Group III (Carbon Dioxide Capture and Storage) of 1 June 2006, European Climate Change Programme II (ECCP II).

14 COM(2007)0002, p. 29.

15 COM(2006)0843, p. 9 f.

16 Council document 7224/07.

17 COM /2008/0018 final Directive 85/337/EEC (EIA Directive); Directives 2000/60/EC (Water Framework Directive), 2001/80/EC (LCP Directive), 2004/35/EC (Environmental Liability Directive), 2006/12/EC (Waste Framework Directive) and Regulation (EC) No. 1013/2006 (Shipments of Waste).

Council adopted the now modified CCS Directive on 6 April 2009. The CCS Directive 2009/31/EC was published in the Official Journal of the European Union on 5 June 2009, and came into effect on 25 June 2009, twenty days after its publication.[18] The CCS Directive (2009/31/EC) must be transposed by Member States by 25 June 2011. In addition to the CCS Directive 2009/31/EC, another Directive equally significant to the regulation and future development of the CCS process came into force at the same time as part of the EU Climate Pact. This was Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009, amending Directive 2003/87/EC. The purpose of this Directive is to improve and extend the greenhouse gas emission allowance trading scheme of the Community.[19] A decisive expansion of the emission trading scheme contained within it is that all activities along the CCS chain will be included in European emissions trading.

6.1.2 Regulatory framework of the CCS Directive (2009/31/EC)

The CCS Directive (2009/31/EC), which extends Article 175 of the Treaty establishing the European Community, is divided into a total of eight Chapters with 41 Articles, and contains two Annexes. In regulating the CCS process, European legislators, and now national legislators (Grünwald 2007, Dietrich 2007, Schulze et al. 2008), faced the question of whether the total process, which could mainly be divided into three steps, should be codified in a directive of their own or whether the various steps should be integrated into existing legal acts. With the CCS Directive (2009/31/EC), European legislators decided to regulate the safety and environmental requirements involved in *CO_2 storage* in a new, separate directive. The *capture* and *transport* of CO_2, on the other hand, are mainly represented in existing European legal acts.

The CCS Directive (2009/31/EC), in which CO_2 storage is comprehensively regulated, is, therefore, of central importance to the future regulation of CO_2 storage by Member States. In view of the risk and hazard potential involved in CO_2 storage, it is the fundamental responsibility of the law, and its legislators, to provide the instruments necessary to guarantee the highest level of safety as well as security for investment and planning (as described by Schulze et al. 2008). With these objectives in mind, the Directive was to provide a detailed web of regulations on the operation, closure and responsibility for storage sites, as well as for post-closure obligations for plants to secure the permanent fate of the CO_2 injected into storage sites (compare Doppelhammer 2008, Dietrich and Bode 2008, Hellriegel 2008, Radgen et al. 2009, Viebahn and Luhmann 2009). It is also significant that CCS technology is classified by European legislators as a so-called “bridging technology” to mitigate climate change, use of which should not, however, serve as an incentive to increase the share of power plants fired with conventional fuels. In addition, the development of CCS should not lead to a reduction in efforts to support energy-saving policies, renewable energies and other safe and sustainable low carbon technologies, both in research and financial terms (compare Recital 4 of the CCS Directive (2009/31/EC)). Thus, at least in this transition period for energy supply, the “bridging period”, CCS technology is equal to other climate protection technologies, in the sense of consolidating and securing energy supply with conventional fuels. The remarks

18 OJ L. 140 of 5 June 2009, p. 114.

19 OJ L. 140 of 5 May 2009, p. 63.

made in Recital 4 of the Directive show that the share of conventional fuels in the energy mix should not be increased through the use of CCS technology.[20]

6.1.2.1 Subject matter, scope and definitions

Chapter 1 (Articles 1 to 3) of the CCS Directive (2009/31/EC) refers to the subject matter and scope, and contains numerous definitions. In keeping with the political aim, the content of the Directive is to establish a legal framework for the capture, transport and – and this is where the focus of the regulation lies – environmentally safe geological storage of carbon dioxide to contribute to the fight against climate change (Article 1(1)). The purpose of the environmentally safe geological storage of CO_2 is the permanent capture of CO_2 so that it prevents negative effects and any risk to the environment and to human health (Article 1(2)). According to Article 2 of the Directive, the geographic scope of the storage of CO_2 applies to the territory of the Member States, their exclusive economic zones and their continental shelves. Furthermore, the Directive may not be applied to R&D projects (intended storage <100 kt CO_2/a). Also, storage in formations extending beyond the territory of the Member States is prohibited, as is the storage of CO_2 in the water column[21].

It is important to understand the definition of "storage" in this context. The injection of CO_2 with the intention of permanently containing it in geological formations does not constitute *storage* from a legal perspective, at least with the intended volumes involved in large-scale use. Such storage always presupposed a reuse of the deposited substance. In legal terms, injecting CO_2 into geological formations without a practical application for its reuse, thus permanent retention in formations, constitutes a *deposit*. Nonetheless, the term "storage" is still used in the definitions contained in Article 3 to describe the deposit of CO_2. This blurring of terms is regrettable, but cannot be changed at the level of European law now that the CCS Directive (2009/31/EC) has come into effect. Also, the term "Carbon Capture and Storage" has already become widespread and established in the English language (compare also Dietrich and Bode 2005). Furthermore, the official German translation of the Directive also uses the word *Speicherung* (storage) throughout.

6.1.2.2 Exploration permits: requirements and conditions for granting permits

Chapter 2 (Articles 4 and 5) determines the basic requirements for the selection of storage sites (Article 4) and the conditions for granting exploration permits (Article 5). According to Article 4(1), Member States shall retain the right to determine the areas from which CO_2 storage sites may be selected and – for competence reasons – Member States have the right not to facilitate storage in parts or in the whole of their sovereign territory. Member States that intend to allow the geological storage of CO_2 in their territory must undertake an assessment of the storage capacity available. For this purpose, a permit for reconnaissance and exploration (*"exploration permit"*) may be granted.

20 Since CO_2 capture leads to an 18–32% increase in consumed fuels (depending on the technology) (see Tab. 10-1), this would signify a corresponding reduction of fossil fuel-fired power plants in the European energy mix on the same scale.

21 However, this does not apply to parts of the North Sea situated beyond the territories of the EU Member States. For this area, tacit agreement has been reached that such areas can be used as storage formations.

The suitability of a geological formation for use as a storage site should be determined through assessing the characteristics of the potential storage complex and surrounding area according to Article 4(3) in connection with Annex I of the Directive using the three-step procedure contained within it. Annex I sets out very detailed requirements for the suitability test of storage sites. For instance, activities around the storage complex that may conflict with it (exploration, production and storage of hydrocarbons, geothermal use of aquifers and use of underground water reserves) must be documented, and extensive geological and geophysical data of the storage complex must be collected. According to Article 3(6), the *storage complex* means the storage site and surrounding geological domain which can have an effect on overall storage integrity and security (that is, secondary capture formations). On the other hand, according to Article 3(3), *storage site* means a defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities (for the geological background, see also Section 7.2.2).

In Article 5, provision is made for exploration to be subject to a permit requirement in national law, insofar as the Member State considers exploration to be necessary prior to storage. No such exploration may take place without an exploration permit. Furthermore, these exploration permits may only be granted for the storage of a limited volume of CO_2, and for a limited period which, however, can be extended. To ensure investment security, the holder of an exploration permit is granted the exclusive right to explore the potential storage complexes. Member States should ensure that no conflicting usages of the storage complex are allowed during the validity period of the permit. Assuming that the large-scale implementation of CCS technology takes place, this exclusive right granted to exploration permit holders is likely to cause problems for them and for national decision-makers responsible for approving applications for permits. This is due to aspects of not only competition law, but also legislation surrounding the awarding of contracts. In the event of there being several applicants for a suitable storage location, a legally secure allocation of the often limited capacities must take place, in view of the high investments involved (compare Viebahn and Luhmann 2009). There are no explicit guidelines in the Directive for national authorities regarding the criteria for such decisions and their weighting, which leaves it up to the Member States to determine the form they will take. Concrete implementations will reveal which instruments and policies the Member States will use to ensure a legally secure “allocation of capacities”. This issue, and the issue of third-party access to the limited capacities, will be explored in further detail in Section 6.1.2.5.

6.1.2.3 Storage permits: requirements and conditions for granting permits

The conditions and requirements for granting storage permits are defined in *Chapter 3* (Articles 6 to 11). According to Article 6(1), Member States must ensure that no storage site is operated without a storage permit; that there should be only one operator for each storage site; and that no conflicting uses are permitted on the site. Member States must ensure that the procedures for granting storage permits (the same applies to exploration permits) are open to all legal entities possessing the necessary capabilities and that the permits are granted on the basis of objective, published and non-discriminatory criteria. This exclusive right of use granted to the holder of an exploration permit is continued in the process for the storage permit, in accordance with Article 6(3), where it is stated that:

- *priority for the granting of a storage permit for a particular site shall be given to the holder of the exploration permit for that site, provided that the exploration of that site is completed, that any condition set in the exploration permit has been complied with, and that the application for a storage permit is made during the period of validity of the exploration permit and*
- *Member States shall ensure that no conflicting uses of the complex are allowed during the permit procedure.*

For the holder of an exploration permit, this means an exclusive right of use to the explored geological formations, usually associated with high investment expenditure. Complications regarding competition law and contract awarding laws can also be expected in connection with granting storage permits, following the procedure for granting exploration permits. These issues will have to be solved with explicit guidelines in the regulations by the Member States, as well as learning by experience from the actual large-scale implementation of CCS (for conceivable conflicts of use, compare Dietrich and Schäperklaus 2009, SRU 2009a).

In addition to the usual documents (name and address of the potential operator, proof of technical competence), applications for storage permits must also include: an evaluation of the storage site and storage complex, an assessment of the expected security of the site, details of the intended quantity to be injected, the prospective sources of CO_2, the composition of the CO_2 to be stored, the intended injection rates and pressures, and the location of injection facilities. Further documents required in the application process are a description of measures to prevent significant irregularities,[22] a proposed monitoring plan (Article 13(2)), a proposed corrective measures plan (Article 16(2)), a provisional post-closure plan (Article 17(3)) and the results of the environmental impact assessment (EIA) carried out in accordance with Article 5 of the EIA Directive (85/337/EEC). Finally, proof that financial security will be valid and effective prior to starting the injection process must also be enclosed with the application. Articles 8 (Conditions for storage permits) and 9 (Contents of storage permits) regulate the conditions that must be satisfied in order for a storage permit to be granted and the contents that should be included in the permits. Some of the content-related requirements governing storage permits correspond to the requirements for exploration permits. Others extend beyond the requirements for exploration permits.

It is particularly worth noting the review of draft storage permits by the Commission in Article 10, which may issue a non-binding opinion on them. This review must be taken into account by the national authorities when issuing permits. Since, however, it is merely a non-binding opinion, national authorities may decide against the opinion of the Commission and should support this with a statement justifying this decision. Unlike with the Commission's draft, the adopted Directive clarifies the fact that it is a non-binding opinion, meaning that the obligation to participate is now reconcilable with the subsidiarity principle.[23] Hence the *"two-man rule"* applies with regard to individual cases.

22 According to Article 3(17), 'significant irregularity' means any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or to human health.

23 In its Resolution of 14 March 2008, Bundesrat Publication 104/08, No. 15, the Bundesrat rightly spoke out against the powers of decision provided for in the Commission's draft (Articles 10 and 18 of the Draft) be-

The highly hazardous potential of CO_2 storage is taken into account in Article 11. If a granted permit is given the right to proceed, this is considerably restricted by precautionary powers of intervention for the authority substantiated by the precautionary principle. The operator must inform the competent authority of any changes planned in the operation of the storage site; major changes must be approved. The granting of these retrospective powers of intervention are called upon, and common legislative practice in the applicable law, in the event of there being potentially hazardous installations simply on the grounds of constitutional law (the state's duty of protection). In addition, the competent authority shall review the storage permit five years after issuing the permit and every ten years thereafter, without prejudice to any further conditions. If any leakages occur or had occurred previously, if conditions of the permit are not observed or are breached, or if it appears necessary on the basis of subsequent scientific findings and technological progress, the competent authority can adjust the storage permit to the altered circumstances or even withdraw the storage permit, depending on the extent of the damage, danger or severity of the breach.

6.1.2.4 Operation, closure and post-closure requirements

The requirements governing the operation, closure and post-closure obligations are set out in *Chapter 4* (Articles 12 to 20). Article 12 determines that the CO_2 to be stored shall *"consist overwhelmingly of carbon dioxide"*, for which reason no waste or other matter may be added for the purpose of disposing of that waste or other matter. As a criterion for the acceptance of a CO_2 stream, i.e. of CO_2 originating from CO_2 capture, it was proposed in the Report of the Environment, Public Health and Food Safety Committee (ENVI) to replace the general wording *"overwhelmingly of carbon dioxide"* with a more specific definition – that *"a CO_2 stream should consist of at least 95 per cent carbon dioxide and should not contain any corrosive substances such as H_2S or SO_2"*. It was also proposed to adjust these requirements to the composition within the review process, should future scientific findings require an adjustment.[24] This proposal for an amendment, which would have gone beyond the degree of purity of at least 90 per cent previously discussed in this respect, was much criticised for many reasons (for example, Radgen et al. 2009; compare also Hellriegel 2008a). As a result, the general clause-like specification already stated in the Commission's proposal – *"overwhelmingly of carbon dioxide"* – in connection with the option granted to the Commission to issue specific guidelines on the determination of the purity criteria on a case by case basis, became part of the Directive. As long as no criteria are issued by the Commission, the Member States have some scope within this to determine specific requirements governing the CO_2 stream.

It is also set out that the operation of the storage site must not have a negative impact on its integrity: there should be no significant risk to the environment or to human health, and no other requirements of applicable Community legislation should be breached. Furthermore, there are some very detailed regulations regarding the monitoring of the installations by the Member States. Monitoring must be based on a monitoring plan that is updated and ap-

cause "such involvement by the Commission in the administrative implementation … (contradicts) the subsidiarity principle." See also (Dietrich and Bode 2008).

24 ENVI, Compromise and consolidated Amendments 1-27 to the geological storage of carbon dioxide and amending Council Directives, 6 October 2008, (PE407.716v01-00).

proved at regular intervals (Article 13(2) in connection with Annex II). Non-routine inspections are also permitted (Article 15). Operators are also obliged to draw up reports (Article 14). Safety procedures must be carried out in the event of leakages or significant irregularities (Article 16).

Articles 17 to 21 contain the provisions governing closure and post-closure, the transfer of responsibility and the financial security arrangements. As has already been mentioned, these must be proved when submitting the application.

The requirements and conditions for the closure of a storage site are determined in Article 17, which states that a storage site shall be closed:

- *if the relevant conditions stated in the permit have been met (a)*
- *at the substantiated request of the operator, after authorisation of the competent authority (b) or*
- *if the competent authority so decides after the withdrawal of a storage permit pursuant to Article 11(3) (c).*

As a matter of principle, the operator is generally responsible for the storage site even after its closure up until the time when the responsibility is transferred to the competent authority (compare Article 18, see below for further information). The post-closure obligations must be fulfilled according to a post-closure plan. This plan is to be designed by the operator based on Annex II No. 2 of this Directive, whereby the preliminary post-closure plan, which must be updated and approved by the competent authority, forms the basis of the final post-closure plan, which also requires approval. Exceptions to these procedural requirements exist in the event of an officially ordered closure of a storage site by the competent authority (compare Article 17(4) and (5)).

After a storage site has been closed, Article 18 gains special significance. Article 18 determines the conditions for transfer of responsibility for decommissioned storage sites. Where a storage site has been closed in accordance with points (a) or (b) of Article 17(1), all legal obligations laid down in this Directive and other European legal acts shall be transferred to the competent authority on its own initiative or upon request from the operator. This is provided that *"all available evidence indicates that the stored CO_2 will be completely and permanently contained,"* that a minimum period (no less than 20 years), to be determined by the competent authority, has elapsed, that the financial obligations have been fulfilled, the site has been sealed and the injection facilities have been removed.[25] The 20-year deadline is the minimum period. The period may only be less than 20 years if certain conditions are met. Longer periods, on the other hand, are possible.

The operator must prepare a report and submit it to the competent authority for the latter to approve the transfer of responsibility. This report must demonstrate that the injected CO_2 has been completely and permanently contained. The actual behaviour of the injected CO_2 must conform with the modelled behaviour, no leakages should be detected and the storage site

25 Interestingly, there was no debate at the European level on whether the period of generally at least 20 years after the closure before responsibility may be transferred suffices to comply with the polluter pays principle applicable in European law. The debate was all the more heated in Germany, for instance, in discussions on the CCS law to be enacted.

must be in a state of long-term stability. In this context, it must be pointed out that, due to a current lack of knowledge, it cannot be forecast for certain whether and when a storage site complies with the criterion of being completely and permanently contained, and what time period should be applied for long-term capture (compare the associated economic implications in Bode and Dietrich 2008). The Directive does not yet provide a specific guideline for the Member States and the competent national authorities to follow in the implementation of this undefined category. However, the Commission is given the option in Article 18(2)(2) of adopting guidelines on the assessment of the factors based on which operators have to prove that the CO_2 has been completely and permanently contained. For legal and investment safety reasons alone, and with the goal of achieving standard legal practice throughout as much of Europe as possible, it is to be hoped that the Commission will soon make use of the option granted to it.

Until such guidelines are issued, the IPCC *Guidelines for National Greenhouse Gas Inventories* from 2006 may act as a useful guide (IPCC 2006).[26] Where the competent national authority is satisfied that the CO_2 has been completely and permanently contained, it can prepare a draft decision of approval of the transfer of responsibility. In accordance with the Directive, the Commission does not only have a representative position with regard to the creation of uniform administrative standards in the procedure for the transfer of responsibility. On the contrary, the competent national authorities must present both the mandatory operator's report about the complete and permanent capture of the CO_2 and the draft decision of approval of the transfer of responsibility to the Commission, along with other associated documents to enable the Commission to exercise its right to issue an opinion on the specific case. Here again, therefore, the "two-man rule" is applied. Conformity with European primary law is guaranteed since, although the opinion of the Commission must be observed in the decision taken by the nation state, the Commission's opinion is not binding for the competent national authorities.

The regulations concerning financial security and the financial mechanisms determined in Articles 19 and 20 are of central importance to closure, post-closure and the transfer of responsibility. The instrument of the provision of financial security is not new, and has often been used in legislation for potentially hazardous environmental uses, such as in the area of waste legislation, implemented by the polluter pays principle. By requiring financial security, the risk to the general public of shouldering the costs incurred through insolvency is averted (Dietrich and Bode 2008, Dietrich 2007).

In accordance with Article 19, the Member States must ensure that proof of adequate financial security can be established by the potential operator as part of the application for a storage permit. This safeguard is to ensure that all obligations arising from the operation of the storage site can be met. This financial security should not only be proved, but also valid and effective before injection work begins. Financial security should remain valid and effective until the responsibility for the storage site is transferred to the competent authority after its closure. The Directive does not contain any additional criteria that would cause the financial security to be used for obligations laid out in this Directive and obligations arising through the inclusion of the storage sites in the emissions trade. Consequently, a certain amount of inse-

26 Compare also (Bode and Dietrich 2008).

curity remains that can only be resolved at Member State level by developing revised administrative or legal practices. Article 19(2) allows a periodical adjustment of financial security. The Article states that this is to *"take account of changes to the assessed risk of leakage and the estimated costs of all obligations arising under the permit issued pursuant to this Directive as well as any obligations arising from inclusion of the storage site under Directive 2003/87/EC."*

Therefore, it becomes clear that the risk of leakage must also be assessed when calculating and costing financial security. There are a number of factors involved in the process of calculating financial security. Firstly, there is the inclusion of potential requirements, such as the obligation to return CO_2 allowances initially generated for CO_2 storage. A second factor which causes uncertainty for investment projects is that the price for allowances is determined by the market and is vulnerable to considerable fluctuations. Therefore, the cost of the security can vary significantly and may need to be adjusted.

Finally, according to Article 20, Member States must ensure that the operator, on the basis of arrangements to be decided by the Member States, makes an additional financial contribution to the competent authority before the transfer of responsibility of the storage site, in accordance with Article 18, has taken place. The amount of the operator's contribution to cover any costs that may arise to ensure the permanent capture of the CO_2 in the storage site should take into account those criteria referred to in Annex I on the characterisation and (risk) assessment of the storage site. Also the elements relating to the history of storing CO_2 relevant to determining the post-transfer must be taken into account. Furthermore, the anticipated cost of 30 years of post-closure monitoring must be included in the security amount. As a result, the criteria for the precise calculation of the amount is formulated in a general way and is not very precise. However, the Commission may adopt guidelines for estimating the security amount. This would be developed in consultation with Member States with the aim of ensuring transparency and predictability for operators. The adoption of uniform standards in this area seems to be pertinent in view of the general criteria given to date, in order to create better investment security for businesses.

6.1.2.5 Third-party access to the infrastructure facilities

Chapter 5 of the Directive (Articles 21 and 22) regulates the requirements with regard to access to the CO_2 transport network and to the storage sites, and how they should be met by the Member States. These regulations appear to be essential to avoid unfair competition, not least against the varied background of the restricted storage capacities in Member States, the exclusive rights of use granted to the holder of a storage permit and the fact that the construction of a CO_2 transport infrastructure will involve high investment expenditure. Accordingly, the right of access to transport and storage capacity is formulated in Article 21(1). This access must be shaped and provided in a transparent and non-discriminatory manner determined by the Member State according to the objectives of fair and open access. However, the right of access is not unlimited. For example, access may be refused where there is incompatibility in the technical specifications of the installations which cannot be reasonably overcome or on the grounds that the transport networks or the storage sites are inadequate. Member States must ensure that any operator who refuses access because of shortcomings in capacity or in transport connections takes the necessary measures to guarantee access to

the site. However, this obligation is restricted since such improvements should be *"economically beneficial"*. If they are not, then the costs of these improvements should be borne by the potential customer. It is incumbent upon the Member States to devise the specific regulatory framework, whereby the nation state's design may draw on existing and transferable experience within the area of access to natural gas transport and storage capacities (Viebahn and Luhmann 2009, Dietrich 2006).

6.1.2.6 Amendments of existing legal acts, general and final provisions

One of the aspects of *Chapter 6* (Articles 23 to 30) is that, in the spirit of cross-border cooperation, the competent authorities must publish a "storage register". Additionally, Member States must make information available to the public relating to the implementation of this Directive. Corresponding necessary amendments or alterations to other existing legal acts of the EC are set out in *Chapter 7* of the Directive (Articles 31 to 37). Due to the amendments, the procedural steps involved in capturing and transporting CO_2, the risk potentials of which only differ slightly to industrial processes that are already practiced and regulated, are also captured in regulatory law.[27] In addition to the CCS Directive (2009/31/EC), CO_2 storage is also assigned to other EC environmental provisions, thus sketching out how it can be systematically implemented by the Member States. The aim is to remove existing legal barriers to the CCS process.

Regulatory coverage of capture and transport

The construction and operation of CO_2 pipelines to transport the CO_2 to storage sites, and the associated booster stations, will be subject to the EIA obligation, as a result of the amendment of Annex I of the EIA Directive (85/337/EEC) laid down in Article 31. This reflects the legislation for the storage sites themselves, and also the installations for CO_2 capture constructed and operated in the power plant and in the industrial process. According to Article 37, Annex I of the IPPC Directive (2008/1/EEC) has been amended so that CO_2 capture installations are covered by the scope of this Directive. This means that safety requirements and risk assessment criteria in the construction and operation of the installations are uniformly defined under European law. A thorough description of the regulatory consequences of the previously described amendments by the CCS Directive (2009/31/EC) is given by (de Graaf and Jans 2009). Tab. 6-1 provides an overview of the specifications of the CCS Directive 2009/31/EC relevant to licensing law.

27 Compare also Recitals 15 and 16 of the CCS Directive 2009/31/EC.

Tab. 6-1 Regulatory and emissions trading laws governing the CCS process

	Capture	Transport	Storage		
			Operational phase	Post-closure phase	
				Before transferring responsibility	**After** transferring responsibility
Permit requirements	-2008/01/EC (previously 96/91/EC IPPC Directive) and -85/337/EEC (EIA Directive)	85/337/EEC (EIA Directive)	CCS Directive	CCS Directive	CCS Directive
Emissions trading	-Not yet determined -Determined in the Directive amending the Emission Trade Directive (Annex I)	-Not yet determined -Determined in the Directive amending the Emission Trade Directive (Annex I)	-One-sided inclusion possible already based on the previous Emission Trade Directive (cf. Article 24 old version) -Determined in the Directive amending the Emission Trade Directive (Annex I)	-One-sided inclusion possible already based on the previous Emission Trade Directive (cf. Article 24 old version) -Determined in the Directive amending the Emission Trade Directive (Annex I)	-One-sided inclusion possible already based on the previous Emission Trade Directive (cf. Article 24 old version) -Determined in the Directive amending the Emission Trade Directive (Annex I)
Leakages	Return of permits	Return of permits	Return of permits	Return of permits	No reimbursement

Directive amending the Emission Trade Directive means: Directive 2009/29/EC (of the…) amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community of 23 April 2009, OJ L 140, 63

CSS Directive means: Directive 2009/31/EC (of the…) on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC and Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No. 1013/2006 of 23 April 2009, OJ L 140, 114

Source: Based on (Dietrich and Bode 2008)

Revocation of procedural obstacles and bans

Procedural obstacles and bans are eliminated by the amendments in Articles 32, 35 and 36. The extension of the Water Framework Directive (2000/60/EC) is regulated in Article 32. According to Article 11(3)(j) of the Water Framework Directive, neither injection of CO_2 nor its discharge into the groundwater was ever permissible, since legislators had obviously assumed it to be a harmful substance. Due to the addition of possible exceptions in accordance with Article 11(3) of the Water Framework Directive, the injection of captured CO_2 for storage purposes into geological formations, which for natural reasons are permanently unsuitable for other purposes, is now, in principle, permitted. Articles 35 and 36 led to the amendment of regulations regarding waste. These amendments were necessary because, according to the

previous predominant opinion in legal literature, CO_2 captured for storage was classified as waste within the meaning of the Waste Framework Directive (2006/12/EC) (Hendriks et al. 2005, Dietrich 2007, Schulze et al. 2008, de Graaf and Jans 2009). Consequently, CO_2 injected into geological formations was classified as the disposal of waste in underground disposal sites, and was not permitted according to Article 5(3) of the Landfill Directive (1999/31/EC) (Hendriks et al. 2005, Dietrich 2007). Based on knowledge of the existing uncertainties, the scope of the Waste Framework Directive has now been restricted by an amendment of Article 2(1)(a) of the Waste Framework Directive. This amendment does not apply to gaseous discharges into the atmosphere any more than it applies to CO_2 that is captured, transported and geologically stored within the CCS process. CO_2 that is to be transported for the purpose of geological storage has now been excluded from the scope of the Waste Shipment Regulation (EC No. 1013/2006) by the amendment of the Regulation provided for in Article 36 (Article 1(3)(h) of the Regulation).

Capture readiness rule and environmental damage

Another regulation, which is of great relevance to the power plant industry and very controversial in the legislative process (compare Radgen et al. 2009, de Graaf and Jans 2009), determines an expansion of the LCP Directive (2001/80/EC) in Article 33. This amendment led to the inclusion of the “capture ready” principle in Article 9a of Directive 2001/80/EC for large combustion plants. Member States must ensure that operators of all combustion plants with a rated electrical output of 300 MW_{el} or more, for which the original construction licence or original operating licence is granted after the coming into force of the CCS Directive 2009/31/EC, have assessed the criteria for retrofitting with CCS technology prior to construction and commissioning. The assessment must cover whether suitable storage sites are available, whether transport facilities are technically and economically feasible, and whether CO_2 capture installations can be retrofitted. If the assessment shows that the CCS criteria have been met, the competent authority must ensure that suitable space on the installation site for retrofitting capture installations is set aside (for more detailed explanations on retrofitting capture ready power plants, see Section 3.2).

The Environment, Public Health and Food Safety Committee (ENVI) was unable to pass its proposal for amendment in the legislative process. This proposal had become known as the “Schwarzenegger clause”. The proposal would have meant that from 2015, power plants with a capacity of over 300 MW_{el} would only have been granted a permit if they were able to guarantee an emission standard of 500 g CO_2/kWh_{el}.[28] Had the proposal been accepted, it would have meant that only new coal-fired power plants that used CO_2 capture within the CCS process would have received permits from 2015. An emission standard of 500 g CO_2/kWh_{el} would have equated to the obligation to use CCS in power plants from 2015. It is assumed, however, that CCS technology will not have been adequately developed and tested by 2015, and that suitable CO_2 storage sites will not have been sufficiently explored and developed (Radgen et al. 2009). In the end, this proposal was not accepted in the legislative process and was not included in the version of the CCS Directive (2009/31/EC) that was ultimately adopted (compare also de Graaf and Jans 2009).

28 ENVI, Compromise and consolidated Amendments 1-27 to the geological storage of carbon dioxide and amending Council Directives, 6 October 2008, (PE407.716v01-00).

In addition, the Environmental Liability Directive (2004/35/EC) has been amended to the extent that the operation of CO_2 storage sites is classified as an occupational activity, which means that operators will have responsibility for fixing any damage that their processing causes, or threatens to cause, to the environment.

The Directive closes with the Final Provisions laid down in *Chapter 8.* These Final Provisions stipulate that the Commission will review the existing regulations by 31 March 2015. They also contain transposition and transitional steps to be undertaken by the Member States (Article 39) and also its entry into force and the addressees of the Directive. The CCS Directive (2009/31/EC) must be implemented by Member States by 25 June 2011.

6.1.2.7 Inclusion in emissions trading and investment incentives

Some economic implications for the development of CCS technology have already been identified. Much work has taken place addressing the regulations to codify CCS technology in terms of safety and the regulatory process. The CCS Directive 2009/31/EC is key in this area. However, these aspects are not the focus of the regulations, and are inadequate for a comprehensive legal framework with which to specifically promote the development of CCS. Reference was made at an early stage (Dietrich and Bode 2005, Hendriks et al. 2005, Dietrich 2007 and Hohmuth 2008) to the possibilities and the conceivable economic incentives of including CCS technology in the European emission trading system, which has established itself as a central international instrument for climate protection. Based on the version of the Emission Trading Directive applicable until Directive 2009/29/EC came into effect, it was only possible to include CCS by way of an opt-in according to Article 24 (de Graaf and Jans 2009, Hohmuth 2008, Dietrich 2007), i.e. only as an exception to the rule.

Consequently, the Directive amending the Emissions Trading Directive (2009/29/EC)[29], also adopted within the European Climate Package on 23 April 2009, contains provisions that could bring significant incentives for the continuing development of CCS technology in Europe, due to the long-term potential of this technology to reduce emissions. The amended Emissions Trading Directive states that activities along the entire CCS process chain are now expressly subject to the emissions trading obligation, following the acceptance of these activities in Annex I of the Emissions Trading Directive in relation to the greenhouse gas CO_2. The raised profile of the emissions trading obligation for CCS brings with it the special investment incentive of not having to submit *allowances* for captured and permanently stored CO_2. However, CO_2 allowances for capturing and storing CO_2 cannot be allocated for free (compare Article 10a(3) and Article 12(3a) of the amended Emissions Trading Directive). The flipside of this is that, in the case of leakages of CO_2 along the CCS chain, the quantity of allowances corresponding to the leaked share of CO_2 must be surrendered. In the event of a leakage, no permanent CO_2 reduction has taken place. If no leakages occur, the operators of CCS installations can freely dispose of, and sell, the share of CO_2 allowances allocated in total for the plant.

In these circumstances, two combined incentives are set for investors and operators of CCS installations. Firstly, operators and investors have a strong interest in the permanence of the

29 Directive 2009/29/EC (of the…) amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community of 23 April 2009, OJ L 140, 63.

CO_2 reduction, and therefore in the safety of the storage sites. This in turn should lead to the implementation of safety investments. Secondly, operators and investors pursue the economic goal of retaining the free disposability and tradeability of the allowances generated by the CCS process, in order to continue to exploit them commercially. The funding system associated with the inclusion in emissions trading is presented in Tab. 6-1. There is a certain amount of insecurity for investors caused by the selected financing mechanism. This is due to the fact that, so far, no general criteria have been established to record, measure and assess leakages from storage sites. Without these criteria, forecasts of quantifiable obligations for returning allowances in the event of a leakage cannot be made.

Regardless of this integrated indirect promotion in the emission trading scheme, Article 10a(8) of the Emissions Trading Directive now provides for another financial mechanism for the construction of 12 demonstration plants by making available allowances in the new entrants' reserve. This financial support for the construction of demonstration plants was added at the last minute of the legislative process *"as a completely new condition"* (according to Viebahn and Luhmann 2009). Pursuant to Article 10a(8) of the Emissions Trading Directive, up to 300 million allowances will be made available until 31 December 2015 *"… to help stimulate the construction and operation of up to 12 commercial demonstration projects that aim at the environmentally safe capture and geological storage (CCS) of CO_2 as well as demonstration projects of innovative renewable energy technologies, in the territory of the Union"*. This provision should lead to or facilitate the acceleration of the implementation of the first commercial demonstration plants. The allowances will be made available to support these demonstration projects that will pave the way for the development, in geographically balanced locations, of a wide range of CCS processes and innovative renewable energy technologies that are not yet commercially viable. The award of the allowances will be dependent upon proof that CO_2 emissions have been avoided.

Projects will be selected on the basis of objective and transparent criteria that include requirements for knowledge-sharing. A further requirement is that no project shall receive support that exceeds 15 per cent of the total number of allowances available. Consequently, if each demonstration plant receives the maximum amount of funding available, seven projects can be funded. With a potential allowance value of € 30/t CO_2, a total of € 9 billion could be paid, hence a maximum of € 1,350 million per project. Deciding on a certain allocation quota is a political decision. The negotiations on the criteria to be applied for the selection of projects and for the allocation of awarded allowances have not yet been concluded. A concrete roadmap for the selection of projects was submitted to Parliament in February 2010 (European Commission 2010). According to a proposal by (Viebahn and Luhmann 2009), funding could be divided between CCS projects and renewable energies in accordance with both technologies' intended share in EU electricity supply in 2050, described in the World Energy Outlook as 29 per cent for CCS and 71 per cent for renewables.

It is also worth mentioning that financial assistance is available for pre-selected CCS projects by way of Regulation No. 663/2009 of the European Parliament and of the Council of 13 July 2009. The intention is to establish a programme to aid economic recovery by granting Community financial assistance to projects in the energy industry, the European Energy Pro-

gramme for Recovery (EEPR).[30] The Regulation establishes a financing instrument for the development of projects in the field of energy in the Community which, by providing a financial stimulus, contributes to economic recovery, the security of energy supply and the reduction of greenhouse gas emissions. *"Carbon capture and storage"* is also listed in the Regulation's sub-programmes (Chapter II, Section 3, Articles 17-21). The eligible projects and envisaged Community contribution are listed in the Annex to the Regulation.[31] Eligible German projects were the power plant project run by RWE AG in Hürth near Cologne and the power plant project initiated by Vattenfall AG in Jänschwalde. The latter was then awarded € 180 million in funding (IZ Klima 2009b).

6.1.3 Summary and assessment

The CCS Directive (2009/31/EC), which is to be transposed into the national law of all Member States by June 2011, along with other modified legal acts, constitutes a comprehensive policy for the use of CCS technology valid in all EU Member States. What is remarkable about the Directive is the short period – not even 18 months – from the presentation of the Commission's draft in January 2008 to its coming into force in June 2009. This rapid turnaround is due to the fact that the CCS process is regarded as a bridging technology, and that CCS, if achievable on a large scale, should be available from 2020 at the latest. Since the specifications of the EU legislation are very detailed in parts, it shows Member States what national CCS policy might look like. However, the Member States, which can classify CO_2 storage in their sovereign territory as wholly or partially inadmissible, are given wide discretion regarding implementation and specification in important areas that affect the regulatory system.

The decision by European legislators to establish a separate, new regulatory system for the storage process, in which the distinctive features of CO_2 storage are to be recognised, should be perceived in a positive way as it should accelerate the arrival of technical feasibility. It is therefore clarified that CO_2 captured in the CCS process and transported to storage sites for permanent storage is not subject to laws surrounding waste. Also, due to the amendment of the Water Framework Directive, the previous ban on injection has now been lifted. The CCS Directive (2009/31/EC) obligates Member States to have safety and environmental aspects of CO_2 storage checked by authorities as a prerequisite to starting work on the site. This covers the entire storage process, from exploration (*"exploration permit"*) and the compression or injection of the CO_2 (*"storage permit"*) to the closure of the storage sites after the completion of storage, for which a permit is also required from the competent authority.

The Directive makes a landmark decision, the details of which were discussed inconclusively beforehand. Responsibility for closed storage sites is usually transferred to the state after 20 years and if the agreed requirements have been met. Most experts agree that this transfer of responsibility is appropriate. Considering the periods (at least 800 years) required for climate-effective storage and the fact that it is virtually impossible for private enterprises, unlike states, to guarantee their existence for such long periods, this 20-year time limit given in the

30 OJ L 200, p. 31.

31 Gas and electricity infrastructure projects (Chapter II, Section 2, Articles 4-11, Annex No. A.) and offshore wind projects (Chapter II, Section 2, Articles 12-16, Annex No. B) count as eligible projects alongside the listed CCS projects.

Directive for transferral of responsibility is very short. However, Member States are able to extend this minimum period for transferring responsibility.

The steps of capture and transport fall within the scope of existing regulations, due to the similarity of activities already practised, and are subject to the safety and environmental requirements therein. With the implementation of the capture ready regulation in the LCP Directive, European legislators have accepted a politically negotiated compromise which states that the use of CCS technology (so far at least) is not an actual requirement for the approval of constructing new coal-fired power plants. Whether this will still be the case after the review process, which is expected to take place by 2015, depends on the technical developments and the political decision that may then be required on the obligatory use of CCS technology.

By integrating the entire CCS process chain into the European emission trading scheme, a tool for CCS will be activated that can be used to provide incentives to investors from both a safety-related and a business management perspective. Important requirements for long-term safe storage and for the investment security necessary for project investors are only described in general and on their merits in the Directive. This relates to, for example, the question of the minimum requirements to be met by the injected CO_2, i.e. its degree of purity, and the parameters on which the financial securities are calculated. Here the Directive has not yet been very specific, although it does provide for the Commission to specify matters by issuing guidelines to define the requirements more precisely.

Neither does the Directive provide guidelines for how authorities should prioritise between different competing projects that require the same geological formation to be present (for instance, geothermal energy or gas storage versus CO_2 storage). It is to be hoped that the Commission will soon make use of the option for specification granted to it in order to establish a standard application of law and investment security.

All in all, the new regulations for CCS technology are suitable for achieving the objectives pursued by it.

6.2 Regulations on CCS concerning the storage of CO_2 in oceans and seas in international law

As well as on the mainland (*"onshore"*), the storage of CO_2 is also possible in geological formations beneath the seabed (*"offshore"*), and it is the intention that this will happen. Regulations pertaining to international maritime law regarding marine environmental protection are crucial to assessing the reliability of such projects. This is because the great majority of these offshore areas are outside of the jurisdiction of nation states (compare the detailed description in UBA 2008, as well as Stoll and Lehmann 2008). National law only applies to such projects if storage takes place within the territories of nation states, i.e. within the exclusive economic zones and in the area of nation states' continental shelves. The possibilities of regulation available to the EU are also restricted to this area (compare also Article 2(1) and (3) of the CCS Directive (2009/31/EC)).

A selection of relevant international agreements are:

- the United Nations Convention on the Law of the Sea of 10 December 1982, which came into force in 1994 (UNCLOS)[32],
- the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972[33] and the 1996 Protocol (London Protocol) to it[34],
- the Convention for the Protection of the Marine Environment of the North-East Atlantic of 1992 (OSPAR Convention)[35] and
- the Convention for the Protection of the Marine Environment of the Baltic Sea Area of 1992 (Helsinki Convention)[36].

Following subsequent amendments to the London Protocol and the OSPAR Convention in February 2007 (for further details, see Stoll and Lehmann 2008 and UBA 2008), CO_2 streams from the CCS process for storage purposes can now be injected into sub-seabed formations once detailed substantive and procedural requirements have been met. The CO_2 must be of the highest purity. There can only be trace amounts of substances associated with the CCS process or the parent substances that cause the minor contamination of the CO_2. Under no circumstance may waste or other matter separate from the CCS process be added to the injected CO_2 for the purpose of disposing of this waste or other matter (UBA 2008).

No amendment has yet been made to the Helsinki Convention, which contains only recommendations and political agreements, rather than legally binding regulations.

6.3 Legal developments outside the EU using the example of the U.S. State of Wyoming and the Australian State of Victoria

Naturally, endeavours to achieve the large-scale use of CCS technology are not limited to Europe and the EU. Many other states are also encouraging its development. Below, the U.S. State of Wyoming and the Australian State of Victoria are taken as examples to briefly describe the legal developments in these states where, more or less, comprehensive legal frameworks have been created specifically for CO_2 storage.

6.3.1 United States of America: The example of Wyoming

In addition to there being numerous R&D activities (compare Section 2.1.3.2), much legal work is taking place in the USA at both federal and state level to regulate CCS technology.

At federal level, the *"American Clean Energy and Security Act"*[37] has been submitted to the parliamentary process as draft legislation, which would substantially change the energy and

32 The United Nations Convention on the Law of the Sea of 10 December 1982 (Federal Law Gazette II, p. 1798), which has been in force since 16 November 1994.

33 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 13 November 1972, 11 ILM 1291 (1972).

34 1996 Protocol to the Convention of Marine Pollution by Dumping of Wastes and Other Matter, 13 November 1972, 8 November 1996, 36 ILM 1, 7-21 (1996).

35 Convention for the Protection of the Marine Environment of the North-East Atlantic of 22 September 1992 (cf. Federal Law Gazette 1994 II, p. 1355).

36 Convention for the Protection of the Marine Environment of the Baltic Sea Area (Federal Law Gazette 1994 II, p. 1355).

37 H.R. 2450.

climate policy of the USA. The aim of the Bill, which was adopted in the House of Representatives on 26 June 2009, is *"to create clean energy jobs, achieve energy independence, reduce global warming pollution and transition to a clean energy economy."* In the section *"Title 1 – Clean Energy"* as a sub-section *"Subtitle B – Carbon Capture and Sequestration",* the draft for the "American Clean Energy and Security Act" contains comprehensive provisions with which existing energy and environmental protection laws (such as the *Clean Air Act* and the *Safe Drinking Water Act*) would be amended to include the special features of the CCS process and to promote CCS technology (for further details, compare Larsen et al. 2009; for general details, compare also Global CCS Institute 2009a). The *American Clean Energy Act* is an attempt to regulate important legal framework conditions at the federal level (Schill et al. 2009). These conditions tackle regulative uncertainties that have been recognised as an investment hurdle, such as with regard to transport, storage and liability in the event of environmental and health-related hazards (Wörlen et al. 2009). The law has yet to be approved by the Senate and has not yet come into effect. In addition, there are a number of other parliamentary bills that aim to regulate the CCS process at the federal level:

- *Carbon Capture and Storage Early Development Act*[38] (for further details, compare Kerr et al. 2009): in the process of adoption, adopted in the House of Representatives on 24 March 2009, not yet law;
- *Carbon Capture and Sequestration Programme Amendments Act*[39]: in the process of adoption, not yet law;
- *American Energy Leadership Act 2009*[40]: in the process of adoption, not yet law;
- *Carbon Storage Stewardship Trust Fund of 2009*[41]: in the process of adoption, not yet law.

It should be noted that there is some overlap in the contents of the aforementioned draft laws. For instance, the regulations contained in the *Carbon Capture and Storage Early Development Act* have been incorporated into the *American Clean Energy and Security Act*. This means that not all of the laws will be adopted.

In July 2008, the U.S. *Environmental Protection Agency (EPA)* proposed regulating federal requirements for CO_2 storage sites, based on the existing regulatory system of *Underground Injection Control (UIC)*.[42] *UIC* regulates the injection of harmful and harmless substances underground. The programme is part of the *"Safe Water Drinking Act",* and defines five classes of injection wells that have different functions. In the draft of the EPA, an additional injection well category (Class VI) has been created for the purpose of CO_2 storage.

The paper also includes criteria for tests to be carried out on storage sites, the construction of injection wells, the monitoring of storage sites and ground water resources in the surrounding area, as well as on the distribution of financial burdens (EPA 2008). In August

38 H.R. 1689.

39 S 1013.

40 S 1462.

41 S 1502.

42 Proposed Rule of the EPA of 25 July 2008, Proposed Rule concerning Federal Requirements Under the Underground Injection Control (UIC) Program for Carbon Dioxide (CO_2) Geologic Sequestration (GS) Wells http://www.epa.gov/fedrgstr/EPA-WATER/2008/July/Day-25/w16626.pdf

2009, the EPA published a "Notice of Data Availability" (NODA), which supplemented the draft from the previous year with newly obtained knowledge. In particular, it contains geological information gathered from the testing of storage sites within *"Regional Carbon Sequestration Partnerships"* and other studies, as well as the results of a published hearing on the rules and regulations published in 2008 (EPA 2009). These regulations will not come into effect before the end of 2010 (Kerr et al. 2009).

Should the Bills become law, there would be a federal legal framework that would largely regulate CCS technology. It remains to be seen how further developments will evolve.

Wyoming deserves special mention regarding regulations on CCS technology at U.S. state level (regarding the developments in the federal states, compare also Pollak et al. 2009; Schill et al. 2009). As early as in March 2008, Wyoming was the first U.S. federal state to adopt a law specifically related to the long-term storage of CO_2, the *enrolled Act No. 25*.[43] As a result of this law, (*"long-term"*) CO_2 storage without simultaneous use of the EOR, EGR or ECBM processes was transferred to control of the *Wyoming Department of Environmental Quality*. The law provides for a regulatory system in which the formal requirements for permits are defined by the *Department of Environmental Quality.* This was integrated into the existing regulatory framework for *"Underground Injection Control"* and drinking water protection legislation (Kerr et al. 2009). Amongst other things, permit applications must include details about financial assurance, a detailed description of the properties of the storage formation, a monitoring plan and a detailed plan for post-closure monitoring, including evidence of safety precautions. In addition, a bonding procedure and other financial assurance methods will be developed and proposed in 2009.

These regulations have since been supplemented by three further laws for the State of Wyoming, with which the aforementioned request for regulation was implemented. In February 2009, the *"House Bill No. 57"* led to existing mining and drilling rights being deemed preferential to planned CO_2 storage. *"House Bill No. 58"* clarifies that the owner and obligor for stored CO_2 and for other substances injected simultaneously with CO_2 is exclusively the person who carried out the injection. Among other things, *"House Bill No. 80"* provides for a *"unitization for geological sequestration sites."* According to this law, under the supervision of the *Wyoming Oil and Gas Conservation Commission,* rights to storage formations belonging to different parties will be rearranged for the purpose of CO_2 storage if 80 per cent of the affected parties agree to such a procedure.

In summary, therefore, comprehensive regulations for the coverage of CCS technology are intended in the USA or, as shown in the example of Wyoming, are already established in law.

6.3.2 Australia: The example of Victoria

In November 2008, the Australian Federal Government adopted the *"Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2008"*, which provides for a regulatory framework for CO_2 storage in *"Commonwealth offshore waters"*. Reference is made to existing regulations from the oil sector in this law. However, these federal regulations apply only to the *offshore storage* of CO_2.

43 House Bill No. 0090.

In 2009, the Australian *"Environment Protection and Heritage Council"* and the *"Ministerial Council on Mineral and Petroleum Reserves"* presented Environmental Guidelines for Carbon Dioxide Capture and Geological Storage. These guidelines contain the first basic details at federal level on environmental assessment, monitoring and the closure of storage sites. According to these guidelines, the monitoring process must include an examination of the storage site prior to the injection of CO_2 and monitoring in the region surrounding the actual CCS injection site. Operators will be required to undertake monitoring, and there will also be independent assessment of their monitoring systems (EPHC 2009; for general information, compare also Global CCS Institute 2009b).

Legal provisions at state level exist for the *onshore storage* of CO_2. For instance, in October 2008, the *"Greenhouse Gas Geological Sequestration Act 2008* (GGGSA)*"*[44] was adopted as a framework law in the Australian State of Victoria, where the testing and development of CCS technology is particularly important, due to there being large deposits of lignite there. The act will come into effect by 1 January 2010 at the latest. This legislation created a legal framework for the storage of CO_2, as well as other greenhouse gases, in underground geological formations for the State of Victoria. The regulations of the GGGSA cover only storage and the steps immediately prior to storage, such as site exploration and the injection of the greenhouse gases. The legislation does not contain any concrete guidelines for the first two steps of the process, i.e. the capture and transport of greenhouse gases. Mention is merely made of *"greenhouse gas infrastructure lines"*, which are defined as pipelines to transport greenhouse gases. These are permitted due to the existing 2005 *"Pipeline Act"*[45]. Storage, on the other hand, is regulated comprehensively, from the exploration of suitable sites to the storage procedure and monitoring. Some specific arrangements remain outstanding, such as where the responsibilities of authorities will lie.

In terms of its legal character, the GGGSA is based on the 1998 *"Victorian Petroleum Act"*, in which (similar) regulations are already established for the exploration and recovery of hydrocarbons in the oil and natural gas industry (Department of Primary Industries 2009). The GGGSA exclusively regulates the storage of greenhouse gases on the mainland (*"onshore"*). This act supplements the provisions of the *"Offshore Petroleum and Greenhouse Gas Storage Act 2008"*[46], a Commonwealth Act that sets up a regulatory system for the exploration, injection and storage of greenhouse gases offshore, outside the 3-mile zone.

Separate permits are required for exploration, storage and monitoring, whereby they build on each other in part:

1. Greenhouse gas sequestration exploration permit

   This permit authorises the holder of the permit to carry out exclusive exploration of the formations for a period of five years (which can be extended only once).

2. *Greenhouse gas sequestration formation retention lease*

   A "retention lease" gives the holder of an exploration permit the exclusive right to use the explored formation for five years if it is suitable for storage but not yet commercially via-

44 Greenhouse Gas Geological Sequestration Act 2008; No. 61 of 2008, Victorian Statute Book.

45 Pipelines Act, No. 61 of 2005 Victorian Statute Book.

46 Offshore Petroleum Amendment (Greenhouse Gas Storage) Act 2008, Commonwealth Act, No. 117, 2008.

ble, but which might become viable to develop within 15 years. This right can be renewed twice for a period of five years each.

3. *Greenhouse gas substance injection and monitoring licence*

   This licence authorises and enables the holder to carry out the storage process. It also requires the holder to monitor the process for the entire period up to the end of the storage phase. The licence is valid until further execution of the permitted activities is cancelled or surrendered by the holder. The right to receive this licence is initially restricted to holders of an exploration permit or a *retention lease* following application to the competent authority. The holder of such a licence must, amongst other things, submit a long-term monitoring and risk management plan for approval by the competent authority (ministry) prior to returning the licence. A further condition for returning the licence is that no risk to lives and health or to the environment may be posed or arise due to the injected CO_2.

For all three types of permit, the GGGSA prohibits the storage of greenhouse gases on land in a national park or a wilderness area.

Furthermore, the GGGSA contains provisions governing the relationship between the land owner and *"occupier"*. According to these provisions, storage activities may not be carried out without the consent of these parties. These parties are entitled to receive compensation if their rights are infringed.

Further *"Greenhouse Gas Geological Sequestration Regulations"* are in the pipeline for 2009. These regulations aim to complete and formalise the framework of the GGGSA. Amongst other things, specifications will be made regarding monitoring obligations and risk management. In addition, obligations about the notification of dangerous situations and the obligation for the permit holder to present an environmental management plan are to be specified in further detail (Department of Primary Industries 2009). It remains to be seen how the current process will develop.

6.4 Developments in other EU Member States using the example of the Netherlands and Poland

Parallel to developments at European level, endeavours to implement CCS technology are also being advanced in the existing energy supply systems within the Member States of the EU. The following examples from the Netherlands and Poland illustrate how these countries have sought to create a suitable legal framework for its implementation. Once again, the final step in the CCS chain is given particular attention.

6.4.1 The Netherlands

In the Netherlands, CCS is given plenty of scope for reducing CO_2 emissions through different climate protection technologies. There are numerous initiatives for the integration of CCS technology in the existing energy supply system (compare Koster 2008 and Koornneef et al. 2008a). This is justifiable since there are plenty of geological formations in the Netherlands that are suitable for the permanent storage of CO_2, particularly gas storage sites that are still in operation or are already depleted (in the majority of cases).

The CO_2 *capture* stage is generally covered by existing Dutch law. Requirements for the onshore pipeline transportation of CO_2 will be determined by an amendment of the *"Algemene Maatregel von Bestuur"* (Ecofys 2007). However, it is only deemed necessary to make amendments in the areas of environmental impact assessment and strategic environmental assessment, which are regulated in the *"Environmental Impact Assessment Decree of 1994"* (Koornneef et al. 2008a, de Graaf and Jans 2009).

Corresponding legislation for the mining industry assists with establishing the legal scope of coverage of CO_2 storage in the Netherlands since it comprehensively regulates the storage of substances in underground formations (Ecofys 2007, Koster 2008). Until now, the special features of CO_2 storage have not been explicitly mentioned in Dutch mining law, the *"Mijnbouwwet"*. The same applies to the delegated legislation in mining law. However, the storage of CO_2 is already adequately covered by applicable mining law (Roggenkamp 2008).

The storage of substances at depths of more than 100 metres below the earth's surface is not permitted without a permit. CO_2 can be included in the regulations for the storage of substances (Koster 2008, Roggenkamp 2008). It is stored at depths of between 800 and 2,500 metres (compare Section 7.2.2). The storage permit contains details about the substances and areas for which the permit is valid, as well as the period of validity. The storage permit should also determine whether the substances should remain underground permanently or should specify the date for their removal. Contrary to the regulations of the German Federal Mining Law, therefore, a differentiation is made between the term "storage" and the express "permanent capture" of the substances underground.

Further permits are ruled out if a storage permit has already been granted for the same formation. Similarly, permits are also refused if an exploration permit or a mineral extraction permit has already been granted for the area. If an application is made for a storage permit, a storage plan must be submitted to the competent authority. Amongst other things, this storage plan must contain a description of the composition and quantity of the stored substances, comprehensive data with regard to the structures of the location of the formations in which the substances are stored and a list of potential hazards that could occur as a result of the dispersion of the injected substance and any conceivable chemical reactions of the substance with the host rock.

Prior to the closure of a storage site, a completion or closure plan must be submitted to the competent authority. This plan must also contain extensive documentation and risk management requirements (Koster 2008). The question also arises in the Netherlands as to how various uses of its geological underground can be reconciled with one another, or how, on the basis of which factors, one of the technologies should be given preferential treatment. One of the main examples of this is the extraction and storage of natural gas on the one hand and CO_2 storage on the other (Roggenkamp 2008). It appears that there has not yet been any amendment to the mining law provisions with regard to the requirements of the CCS Directive (2009/31/EC), whereby the connecting factor of the necessary legislative amendments are considered to be in mining law (Koster 2008).

In addition to the necessary mining law permits, the *environmental law* requirements in the Netherlands must also be considered. The special issues and requirements of the CCS Directive (2009/31/EC) and the other amended legal acts of the EU associated with the CCS process have not yet been explicitly accounted for in environmental legislation. The Dutch

Environmental Management Law (*Wet milieubeheer*) is of particular importance to environmental law requirements. In the Environmental Management Law, direct reference is made to the requirements of the IPPC Directive and the LCP Directive. This means that no extensive amendments are deemed necessary to implement the further amendments of the IPPC Directive and the LCP Directive associated with the adoption of the CCS Directive (2009/31/EC) for the CCS process (de Graaf and Jans 2009).

Amendments and clarifications are also considered necessary for Dutch law in view of the amendments and supplements to the EIA Directive with which the various steps involved in CCS, sometimes dependent on the attainment of stipulated volumes and dimensions, are introduced (de Graaf and Jans 2009, Koornneef et al. 2008a). Definite proposals have already been submitted with regard to the requirements that exist in the Netherlands due to the environmental impact assessment and a strategic environmental assessment (Koornneef et al. 2008a). Due to the regulations contained in the CCS Directive (2009/31/EC) on the amendment of the Waste Framework Directive and other waste law provisions, according to which CO_2 is expressly removed from the scope of waste law, amendments to waste legislation in the Netherlands are considered to be necessary (de Graaf and Jans 2009).

The Dutch Environmental Licensing (General Provisions) Bill (*Wabo*) aims to integrate project approval into just one single permit. Germany has also tried to streamline the process in this way through the framework of codifying the Environmental Law Code, in addition to a water law approval procedure, if required. The subject of the licensing procedure is all about environmental relevance, spatial planning and construction law requirements. One single authority will be responsible for the licensing procedure. It is being debated whether the multi-link CCS process can be viewed as one activity for which one single permit is required, particularly since the mining law permit for CO_2 storage is not the subject of the draft law according to applicable law (de Graaf and Jans 2009). It remains to be seen how the further developments will evolve.

In Regulation No. 663/2009 of the European Parliament and of the Council of 13 July 2009 on a European Energy Programme for Recovery (EEPR, see Section 6.1.2.7), three Dutch power plant projects – two in Rotterdam and one in Eemshaven – were classified as eligible for funding. The E.ON project in Maasvlakte, the industrial area of Rotterdam, was finally awarded funding of € 180 million (IZ Klima 2009b).

6.4.2 Poland

In Poland, CCS technology is considered to have great potential for reducing CO_2 emissions. The CCS Directive (2009/31/EC) has not yet been transposed into Polish law, but should be implemented by 2011. The discussion on how best to set about doing this has only just started. Poland is interested in the rapid development of CCS technology to the level of large-scale feasibility, the foundations of which should be laid between 2010 and 2012.

The report on the *"Energy policy of Poland up to 2030* (*Polityka energetyczna Polski do 2030 roku*)*"*[47], was presented on 10 November 2009, following consultations with the Polish Coun-

47 Accessible at: http://www.mg.gov.pl/NR/rdonlyres/5474D2C2-2306-42B0-B15A-7D3E4E61D1D8/56330/PE.pdf.

cil of Ministers. In this report, the use of CCS technology, together with other innovations in energy efficiency and the increased use of renewable energies, was expressly mentioned as an important building block in Poland's future energy infrastructure. Whilst this report is not a binding roadmap, it contains political targets designed to be adopted in the short term.

In Section 7.2 of the report under the title *"Measures to limit negative environmental impacts arising in the area of power generation",* relating to CCS technology, it is stated that the introduction of uniform standards on the use of CCS technology for commercial use is planned with regard to the construction of new coal-fired power plants. Poland intends to take an active role in implementing the goal of the EU Commission to establish demonstration plants for CCS technology and in the area of renewable energies across Europe. One CCS demonstration plant is to be constructed in Poland (power plant in Belchatów). In addition, R&D into CCS technology and into the use of CO_2 as a raw material in industry will be encouraged.

In August 2009, the Polish Ministry of Economy presented a first draft of a programme to formalise and implement the report "*Energy policy of Poland up to 2030"* for 2009 to 2012.[48] CCS technology is mentioned in the report in Sections 6.5 to 6.7. Within this, it is intended to work with the EU Commission to develop consolidated standards in the use of CCS technology. To support this, it is intended to transpose the CCS Directive (2009/31/EC) into Polish law by 2011. Both tasks fall within the remit of the Ministry of Economy.

In addition, it recommends that this programme should be supported by public information campaigns (by 2012). Also, a monitoring programme for the underground storage of CO_2 will be devised and implemented. The Ministry of Environment is responsible for both tasks. A further aim is to realise the demonstration projects and to devise possibilities and solutions for the further development of "*clean coal technologies"* within an operative programme "*Infrastructure and Environment"* in 2009 and 2010 and a national programme in 2010. The possibilities and opportunities for CCS technology in the processing of natural oil and natural gas are to be investigated and researched.

On 4 November 2009, the Polish Ministry of Environment submitted a first draft to implement the CCS Directive (2009/31/EC).[49] The new regulations mainly affect the Polish Mining and Geology Act.[50] Poland is pursuing the path of implementing the CCS Directive's (2009/31/EC) stipulations by connecting it to existing and established regulation regimes. There are no plans to enact a separate CCS law in Poland.

According to the CCS Directive (2009/31/EC), the activities involved in the selection of storage sites ("exploration permit") and the storage process itself ("storage permit") are subject to authorisation. Polish legislators intend to implement this stipulation using two "licences", to be issued by the Polish Ministry of Environment. All applicants must be commercially active enterprises, which fall within the scope of the Law on Economic Activities[51]. While the CCS

48 "Programme to implement the energy policy of Poland 2009-2012 (Program działań wykonawczych na lata 2009-2012)", accessible at: http://www.mg.gov.pl/NR/rdonlyres/5474D2C2-2306-42B0-B15A-7D3E4E61D1D8/56333/zal3PDW.pdf.

49 Accessible at: http://www.mos.gov.pl/g2/big/2009_11/1c483d65bb96ad1332c18842f9bd9bf7.pdf.

50 Mining and Geology Act of 4 February 1994, Dziennik Ustaw (Dz. U., Polish law gazette) No. 27, Pos. 97.

51 Law on Economic Activities of 2 July 2004, Dz. U. No. 173, Pos. 1807.

Directive (2009/31/EC) does not apply to research-based plants with a total storage volume of under 100,000 tonnes of CO_2, the amended Mining and Geology Act does not provide for such a restriction.

Explorations of both geological formations and underground storage[52] can only be carried out if a written licence has been issued by the Ministry of Environment. An environmental impact assessment is an essential component of the application process for the choice of storage sites. Not only the mayor of the communities in which the storage sites are located must be involved in the process – the EC Commission, which can issue a statement on the project within four months, also has a say in the matter, complying with the stipulations of Article 10 of the CCS Directive (2009/31/EC).

The draft law also determines the information applications should contain and the supporting documents to be submitted, which go beyond the stipulations in Article 7 of the CCS Directive (2009/31/EC). If an application is made for a "storage licence", a working plan for the underground storage and a monitoring concept must be presented.

In accordance with Article 7 of the CCS Directive (2009/31/EC), applicants must enclose a proposal for a monitoring plan, a corrective measure plan and a post-closure plan with their application. According to Polish regulations, these plans will be combined into a single plan, the working plan for the underground storage of CO_2. This plan is subject to approval by the competent supervisory body (the Polish State Mining Authority), and becomes legally binding as an annex to the licence. The plan must be updated at least every five years.

In addition, applicants must enclose supporting documents to prove they have sufficient financial means within the meaning of Article 19 of the CCS Directive (2009/31/EC) with their application for a "storage licence". This financial security is paid into a "subsidiary account" of the Fund for Environmental Protection and Water Management, as regulated in the Environment Protection Law[53]. The security is made available to bring a proper end to the activity, etc., in the event of the insolvency of the company, if it terminates its activities or if the licence is revoked. The guarantee comprises a repayable and a non-repayable part. The costs of decommissioning and 20 years of monitoring, or any costs for associated maintenance work are repayable. The costs of 30 years of monitoring once responsibility has been transferred to the state are not repayable. Any associated maintenance work or activities to be carried out by the state instead of the actual party responsible are not repayable either.

Amongst other things, the licence determines how the work for which the application was made will be carried out, the exact boundary of the storage site, the limits to which the work can be performed, the period for which the licence is granted and the earliest date on which work can commence. In addition, the licence may also contain details on environmental protection or special safeguarding measures (such as special monitoring requirements or use of the best technology available). Furthermore, the licensed storage sites may not be larger than 1,200 km².

52 In the draft law, the term "składowanie = storage/deposit" is used. The term "storage = gromadzenie" is not mentioned in the draft, contrary to the choice of terms in the CCS Directive (2009/31/EC) in European law and the official Polish translation.

53 Environment Protection Law of 27 April 2001, Dz. U. No. 62, Pos. 627.

If the future stipulations to be contained in the Mining and Geology Act are not met, the application for a licence will be rejected. The application may also be rejected if it breaches the Law on Economic Activities. Licences can be transferred to third parties, provided they are able to meet the conditions and any other stipulations.

Any company that can prove it has the appropriate knowledge and experience can be an operator of an underground storage site. The company in possession of a licence to explore geological formations and to store CO_2 underground is the rightful owner under mining law, and is therefore entitled to the mining rights. The company must also fulfil its documentation obligations.

The provisions on the underground storage of CO_2 are regulated separately in a new section of the Mining and Geology Act. In particular, they comprise details on how to determine sites, on commissioning underground storage sites, reports to be submitted by the operator, inspection, measures to be taken in the event of irregularities, closure, post-closure and registration obligations and the transfer of responsibility.

It is intended to make the storage of CO_2 subject to charge, which is of particular interest against the backdrop of the current debate in Germany on a “storage fee”. Sixty per cent of the fees will be awarded to the communities containing the plants. Forty per cent of the income will be allocated to the Fund for Environmental Protection and Water Management.

The transposition of the stipulations of the CCS Directive (2009/31/EC) demands not only an amendment of the Mining and Geology Act, but also amendments to other laws, such as the Law on Economic Activities, the Environmental Impact Assessment Act[54], the Energy Act[55], the Environment Protection Law and the Environmental Damage Act[56]. A provision will be incorporated into the Waste Act[57], stipulating that this law shall not apply to the underground storage of CO_2. The purpose of these measures is to transpose the stipulations of the Directive.

Even in the planning permission process, all operators of new power plants with a capacity exceeding 300 MW must comment on how CO_2 should be captured and stored in future. It is assumed in Poland that energy costs will increase by over 60 per cent following the large-scale deployment of the CCS process. The practical implementation is particularly interesting to energy companies that will have to purchase all of their emission allowances by auction after 2020.[58]

According to Regulation No. 663/2009 of the European Parliament and of the Council of 13 July 2009 on a European Energy Programme for Recovery (EEPR, see Section 6.1.2.7), the power plant project by PGE at the Belchatow site was classified as eligible for funding; it was finally awarded € 180 million in funding (IZ Klima 2009b).

54 Law on Environmental Impact Assessment, Environmental Information and Public Participation in Environmental Procedures of 3 October 2008, Dz. U. No. 199, Pos. 1227.

55 Energy Act of 10 April 1997, Dz. U. No. 54 Pos. 348.

56 Environmental Damage Act of 13 April 2007, Dz. U. No. 75, Pos. 493.

57 Waste Act of 27 April 2001, Dz. U. No. 62, Pos. 628.

58 http://biznes.gazetaprawna.pl/artykuly/371121,4_5_mld_euro_rocznie_za_magazynowanie_co2.html.

6.5 Legal framework for CCS technology at the level of national law

This Section is only available in the German version of the Final Report. A summary is given in the English version.

The applicable German law has been inadequate to the task of legislating for the different procedural steps of the CCS chain. The greatest problems arise in the field of CO_2 injection, solely aimed at permanently removing CO_2. For this reason, projects concerning the permanent storage of CO_2 are only permitted in a few constellations in accordance with the applicable law.

On the basis of this finding and the specifications of the CCS Directive (2009/31/EC), a draft CCS Law intended to encompass the whole CCS process for speedy implementation in Germany was submitted by the German Federal Cabinet in April 2009. In the end, the Bill was not adopted. Overall, the CCS Law was recognisably guided by achieving a transposition close to the specifications of the CCS Directive (2009/31/EC), intending to meet not only environmental and safety requirements, but also the demands governing the necessary investment and legal security for CCS projects. This objective was not fully achieved by the draft CCS Law. The CCS process is not expressly called a transitional technology in the draft of the Carbon Dioxide Storage Act. Although this is not a violation of the guidelines of the CCS Directive, critics in Germany demand a systematical change by declaring the CCS Law as a research law that can be used to enable the exploration of CCS in a limited number of demonstration plants. It is clear that, from today's perspective, the CCS process, and in particular the question of the permanence of CO_2 storages sites, cannot be answered conclusively, and certainly not in general terms.

The provisions for detecting, assessing and resolving conflicts concerning underground usage resulting from the large-scale use of CCS technology were also inadequate. The provisions provide for solutions to individual cases, rather than for extensive, preventive planning. In a renewed attempt at creating legislation, the reservations of the potential federal "*storage states*", underestimated in the "first attempt" at devising a CCS Law explored here, should be taken seriously. The authors are also critical of the regulatory approach because it failed to regulate and specify fundamental legal decisions in a parliamentary act. Instead, they were moved to the level of ordinances. However, the relevant ordinances were not tabled at the same time as the Act. In view of the distinct conflicts emerging between land owners and those with an interest in underground uses, this legal relationship should also be regulated so that the risk of legal uncertainty is mitigated, and all parties are aware of their rights and obligations. If the question of the suitable time to transfer responsibility to the respective federal state is explored in further detail, the general deadline of a minimum of 30 years after the decommissioning of the plant, as stipulated in the draft of the Carbon Dioxide Storage Act, seems appropriate. It is not recommended that new and extended, or shortened clauses, are established in addition to the technology clauses currently used with standards that were formalised over a long period in practice through jurisprudence. This would cause unnecessary legal uncertainty.

7 Analysis of the options for storing CO_2

7.1 Objectives

Underground storage of the greenhouse gas CO_2 is crucial to the whole CCS process chain.The objectives of the analysis were therefore to:

- systematically analyse and compare existing capacity estimates with regard to their methods and assumptions;
- present a cautious, conservative estimate for the effective capacity within the definition of a lower limit for orientation purposes for potential investors and political decision-makers.

This would be not only for Germany, but also for neighbouring countries where CO_2 from Germany could possibly be stored.

Using a scenario analysis, a typical “what-if” examination was conducted in which cautious estimates and assumptions were pooled. Rather than basing the analysis on new geological data, it uses findings given in the literature. It should be pointed out that, due to a lack of practical experience of injecting CO_2, and also a lack of data, both the conservative calculation presented here and existing estimates should be treated with caution. Such general estimates can only be rough generalisations, and need to be supplemented by detailed investigations of individual storage structures.

In this chapter we will first give an overview of the formations potentially suitable for storing CO_2. After describing the storage mechanisms, we will present the methodology used to estimate capacities. In the central Sections 7.5 and 7.6, we go on to analyse the CO_2 storage capacities for Germany and other European countries that are potentially suitable for storing CO_2 from Germany. Following a brief overview of atlases and cadastres regarding CO_2 storage capacity, we finally consider the role of enhanced oil recovery for CCS.

7.2 Geological basics

7.2.1 Formations for CO_2 storage

Deep saline aquifers

The injection of CO_2 into deep saline aquifers is generally considered to be the most important option for storing CO_2 because these formations are expected to offer the greatest potential (May et al. 2005). Aquifers are deposits of rock saturated with drinking water or brine in their porous sedimentary strata. Only saline aquifers with saliferous ground water are considered for the storage of CO_2. The very slow flowing movement of the ground water (approximately a few cm per year) prevents the fast migration of the CO_2 within the aquifer. Such saline aquifers are widespread. In Germany, they are mainly found in the North German Plain and the North Sea. It is generally assumed that the injected CO_2 would remain safe underground for the long term due to dissolution and mineralisation.

Oil and natural gas fields

Depleted oil and natural gas fields are ideal for storing CO_2 underground. Carbon dioxide is injected below the structure, causing it to rise, due to the difference in density (similar to the formation of oil and natural gas). It then collects beneath the roof. Depleted oil and natural gas fields have shown they have caps that have been suitable for millions of years. Equally, these caps are assumed to be impermeable to greenhouse gases. However, it is important to note that CO_2 has different chemical properties to those of oil or natural gas, which could cause problems. Above all, it is important to mention that the formation of carbonic acid, caused by the dissolution of CO_2 in the water, creates an acidic and therefore corrosive environment (Hunt 1995, Ennis-King and Paterson 2007, Kharaka et al. 2006).

The initiation of the commercial application of CCS could be triggered by the expansion of *tertiary oil recovery*, which has already been applied for decades in the USA. Here, naturally occurring CO_2 is injected into oil fields to enhance extraction (enhanced oil recovery, EOR). Using this method, some of the oil is forced out of the formation. However, the CO_2 also blends with it, reducing the viscosity of the oil and making recovery easier. The CO_2 must then be separated from the oil. Further information on EOR and the environmental impacts associated with it can be found in Section 7.8.

Another similar technology is *enhanced gas recovery* (EGR) using CO_2, which, as yet, is a long way from becoming commercially available (Grünwald 2008).

Deep coal seams

Another option under discussion is the injection of CO_2 into deep uneconomical coal seams and depleted coal mines. When the gas comes into contact with the surface of the coal, it is absorbed and, therefore, bonds to it. This reaction, successful in a laboratory setting, must first be proven in natural environments in a series of extensive experiments. So far, in situ tests have encountered severe problems. For this reason, the option for storing CO_2 in coal deposits has until now been declared as unfeasible because of safety concerns and storage efficiency issues (Shi and Durucan 2005). This storage option is not being considered in Germany because the underground is highly fissured due to coal production, and it appears impossible to guarantee controlled injection (May 2003).

7.2.2 Characteristics of suitable reservoir rocks

Reservoir rock must meet certain prerequisites if the deposit of CO_2 is to be successful. The central criterion is an *impermeable cap rock* to prevent the injected gas from escaping towards the surface (see Fig. 7-1 in which the example of an aquifer is given). In addition, suitable injectivity must be guaranteed; in other words, the quantity of CO_2 that needs to be injected must reach the subsurface in the stipulated time. This condition is known as *permeability*. In contrast, the ratio of pore space to the total volume of a rock is defined as its *porosity*. The injected CO_2 can only spread into the depression and provide sufficient space for subsequent quantities if the pores are connected to one another. If the pores are too small, an extremely high level of pressure must be applied to allow the gas to pass through the rock structures.

These two parameters should have an appropriate ratio to one another to enable a large proportion of the permeable pore rock (also called the “net-to-gross” ratio n/g) to be used for the storage of CO_2. In other words, porosity and permeability have a decisive influence on the injection rate, which indicates how much CO_2 can be injected in the underground per unit of time. Although the maximum injection rate is initially irrelevant in the analysis of the storage potential, it could be a limiting factor in a concrete CO_2 storage project.

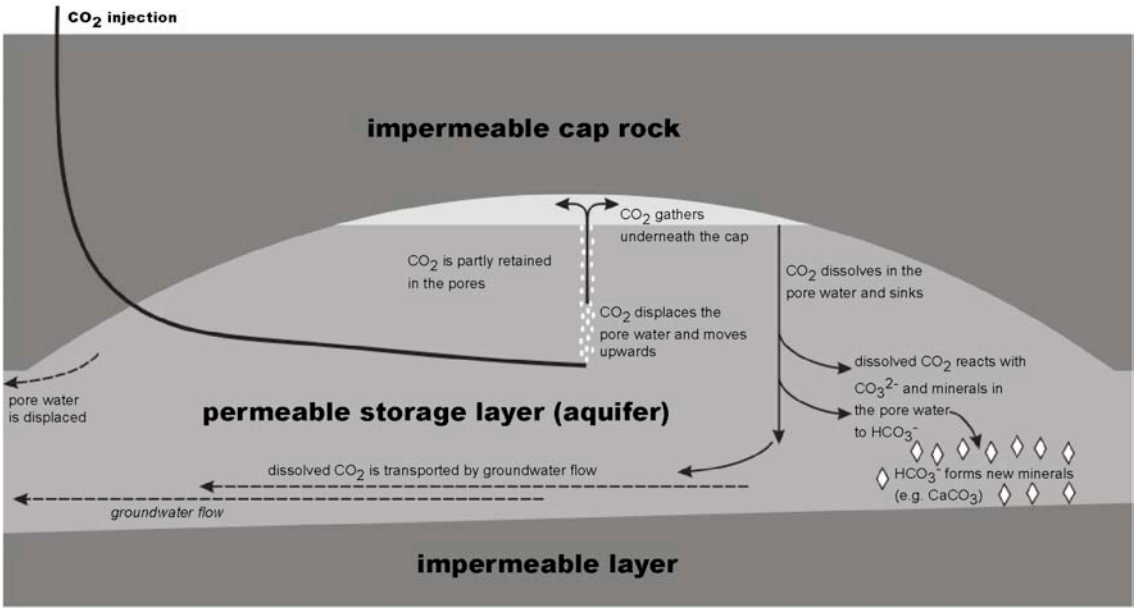


Fig. 7-1 Schematic diagram of an aquifer with permeable pore rock and sealed layers from above and below

Source: UBA (2008)

The deeper the formation, the thicker the sedimentary layers above the formation, which leads to an increase in pressure and temperature. Under average conditions, the increase in pressure *(pressure gradient*) is 10–12 MPa/km (North 1985), and the rise in temperature (thermal gradient) is 25–30° K/km. Pressure and temperature determine the phase state of a substance. This phase state is closely related to the density of substances because high pressures compress fluids. Fig. 7-2 shows how the relative volume of CO_2 decreases with depth (reduction of the quader volume by up to 2.7 per cent of the original value).

The density of CO_2 is therefore another crucial parameter for effective storage. It is wise to store CO_2 underground in its supercritical state (600–700 kg/m^3) because compression takes place many times over compared with its gaseous state (2 kg/m^3) (Bradshaw et al. 2005). Therefore, much more CO_2 per spatial unit can be stored. This state is achieved from a critical temperature of 31.1°C and a critical pressure of 7.4 MPa.

If the critical point is exceeded, the phase boundary between gas and fluid disappears. These conditions are found in reservoirs at a depth of 800 m. Since from this depth density does not change as starkly as in the first 800 m, it is also deemed to be the *minimum storage depth*.

The *maximum depth* is determined by the steady decline in porosity and permeability with increasing pressure. From a depth of 2,500 m, these parameters are reduced to such an

extent that it becomes extremely difficult to inject CO_2 into the formation (Vangkilde-Pedersen et al. 2008). For this reason, suitable storage reservoirs would be located at a depth of between 800 and 2,500 m.

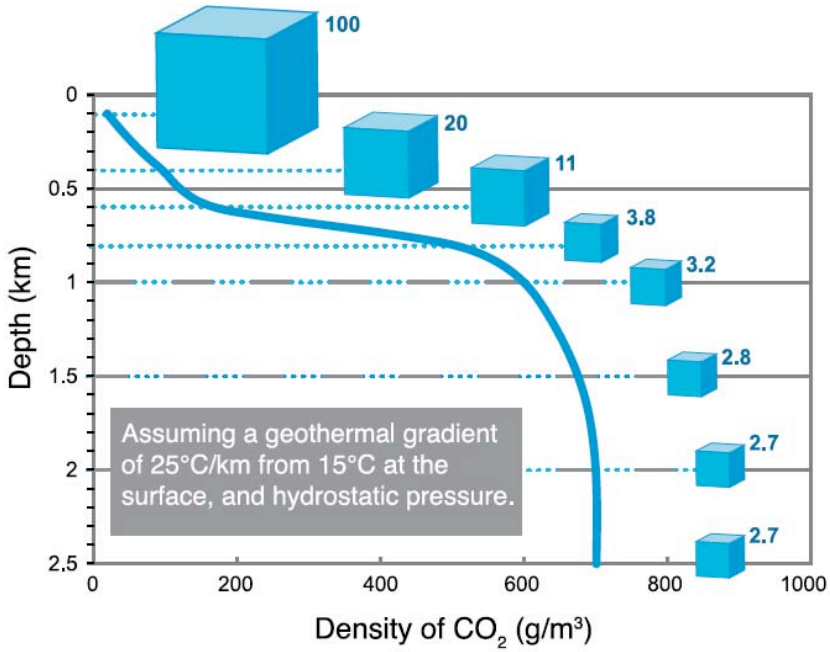


Fig. 7-2 How the density, and hence the volume, of CO_2 changes with depth (the density's unit must be kg/m^3)

Source: Based on IPCC 2005

In aquifers, the bed rock in this region is water-saturated. The water has a very high salt content and, under average conditions, contains over 300 g/l dissolved substances. This water must be displaced or, if insufficient space is available, compressed to enable sufficient quantities of CO_2 to be stored. If the pressure cannot be increased any further, then the water must be extracted from the formation.

Tab. 7-1 shows the maximum and minimum values of the decisive parameters for selecting storage sites.

Tab. 7-1 Overview of the characteristic properties of suitable reservoir rocks (minimum, maximum and optimum conditions)

Property		Unit	Minimum	Optimum	Maximum	Example *
Permeability	Cap rock	mD	as low as possible		1 - 10	
	Reservoir	mD	200	> 300	> 1,000	100–700
Porosity	Cap rock	%	-	< 10	10	
	Reservoir	%	10	20	30	18.7
Thickness	Cap rock	m	20	> 100	infinite	infinite
	Reservoir	m	20–50	100	300	200
CO_2 density		kg/m^3	500	700	750	650
Depth		m	800	1,200	2,500	200–3000

* = properties of a Lower Trias reservoir (UK), average values following (Bentham 2006)

Source: Höller 2009

7.2.3 Open and closed formations

When considering the type of storage sites, a differentiation can be made between closed and open *structures* and closed and open *systems*. In the following, we first describe geological *structures*.

Fig. 7-3 shows the differences between structures using examples from oil and natural gas geology. The most well-known type of *closed* structure, also called a trap, is an anticlinal arch structure, which can be best imagined as a subterranean hill (illustration (a)). In addition to these structural traps, other hydrocarbon storage sites can be found in faults (b) or stratigraphic traps (c). Furthermore, illustration (d) shows accumulation in salt domes. Since these closed structures have previously retained oil and natural gas, they are equally well suited for the storage of CO_2. In this case, the CO_2 is accumulated as mobile phase beneath the cap rock.

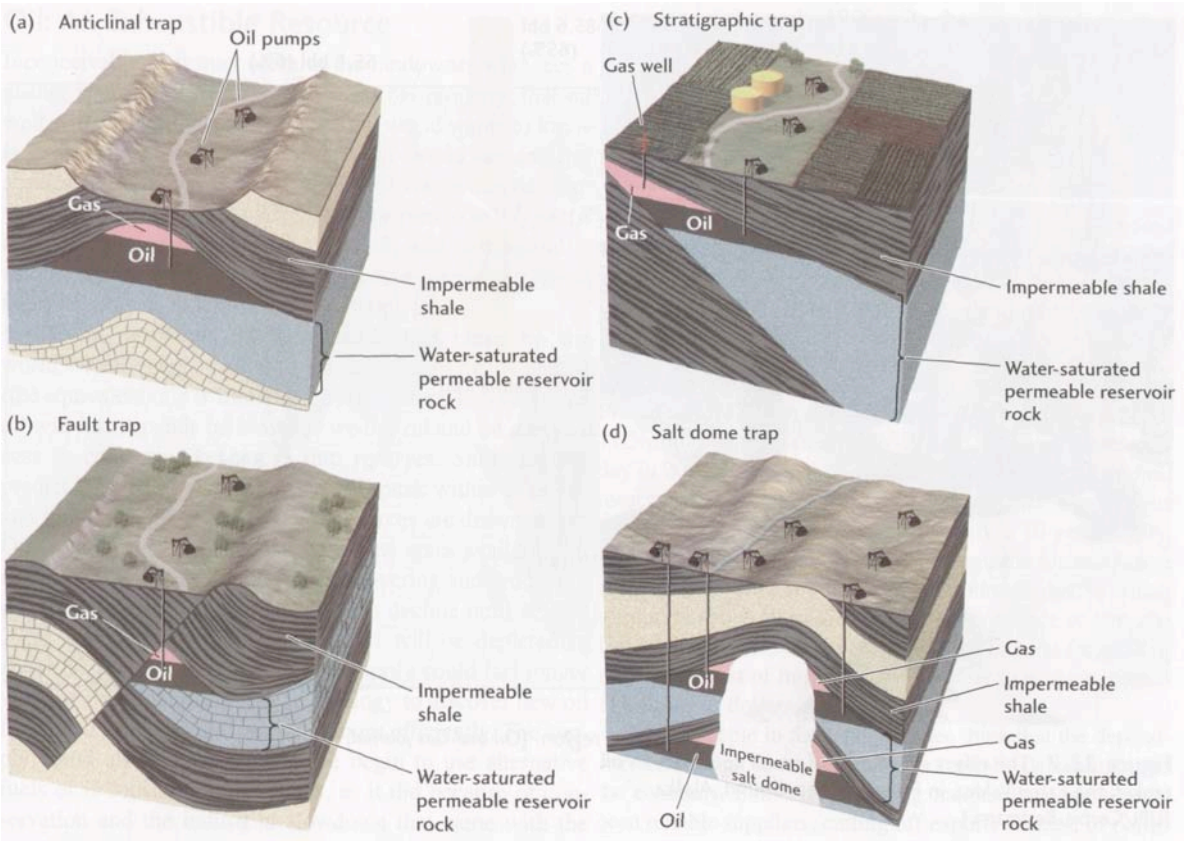


Fig. 7-3 Overview of various geological structures in which oil and natural gas have accumulated
Source: Grotzinger and Jordan 2010

In addition to anticlines, there are also rocks with layers that dip towards the centre of the structure, so-called syncline structures. These syncline formations are *open* towards the top, which can lead to the further dissipation of CO_2 underground, increasing risks to safety (Dose 2008). A syncline and an anticline structure are shown in Fig. 7-4.

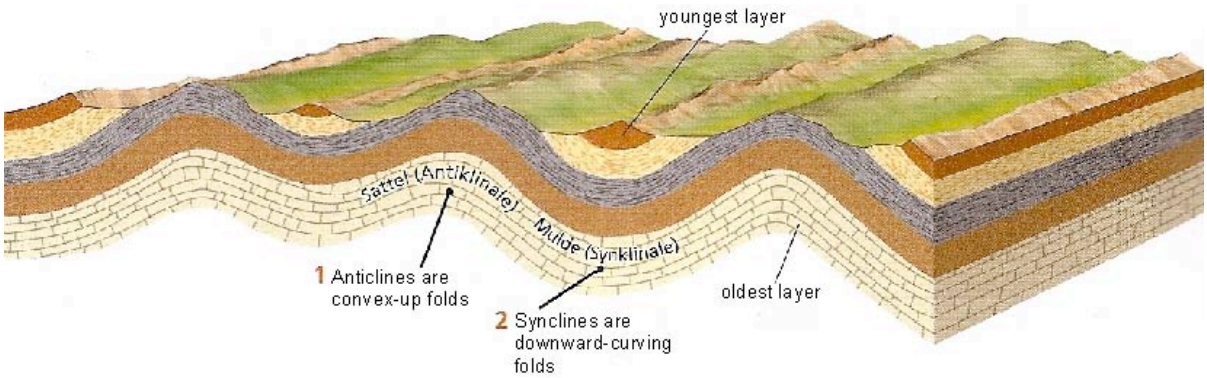


Fig. 7-4 Geological formations to explain the terms anticline and syncline

Source: Grotzinger and Jordan 2010

Structures can be part of an open or closed *system* (Fig. 7-5). In both cases, the water would be compressed and displaced after injection. In a *closed* system, an injection of CO_2 would increase the pressure within the system, and the compression would make space for the gas.

If the structure is connected to a large aquifer, it is described as an *open system* (bottom left in Fig. 7-5). In this case, the displacement process prevails during injection. The quantity of salt water that can be displaced out of the formation without having a negative impact on humans and the environment is determined by efficiency. Only a certain amount of CO_2 can be injected before a potentially catastrophic outcome, such as the salinisation of potable water reservoirs or the seepage of salt water to the surface. The much discussed term “leakage” is then given a new dimension because it is no longer only the CO_2 that could enter the atmosphere from the underground, but also deep ground water with a very high salt content.

In the legal definition of Section 6.1.2.2, the term for the structure was called the *storage site*. The whole system in which this site is located is called the *storage complex*.

It is relevant to make a distinction between these two terms, particularly when the possible leakage of CO_2 is involved. The German Federal Environment Agency (UBA 2009) views even the escape of CO_2 from the *storage site* as a leakage, whereas the CCS Directive 2009/31/EC only defines leakage when the injected gas leaks out of the *storage complex*.

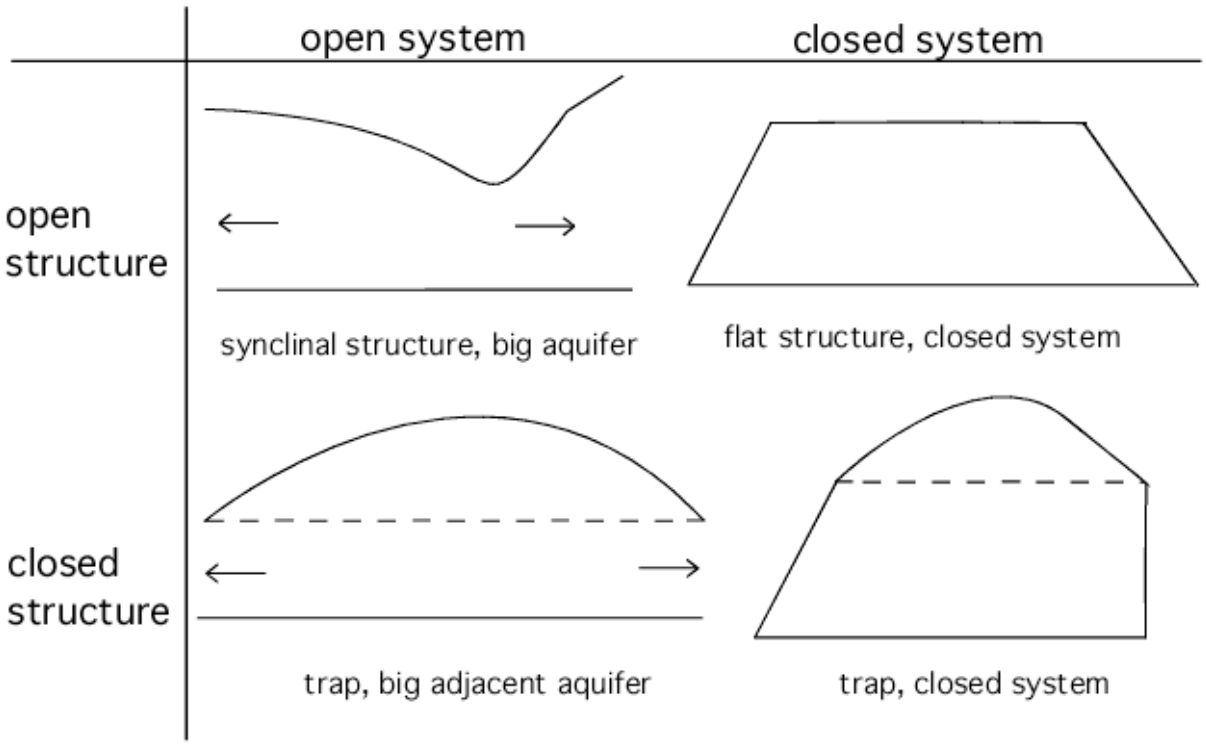


Fig. 7-5 Schematic diagram of examples of open and closed structures in open and closed systems
Source: Höller 2009

7.3 Storage mechanisms

Once it has been injected below the surface, the CO_2 can be kept there using a variety of techniques. Firstly, the pore water is displaced by the carbon dioxide. CO_2 rises in this formation because it has a lower density than the surrounding salt water. During the process, a small part of the CO_2 is stored in underground capillary pores. As soon as the CO_2 reaches a cap rock, it accumulates there in a structure as a mobile phase (compare Fig. 7-1). CO_2 is gradually dissolved in the salt water at the boundary surface to the layer of water, and carbonic acid is formed. Since the salt water containing carbonic acid is heavier than CO_2-free salt water, it sinks. In this way, even more CO_2-free water can flow into the formation and absorb CO_2. In the long term, all of the mobile CO_2 is dissolved. The mineralogical precipitation of carbonates occurs only after CO_2 saturation in the water if sufficient cations (e.g. calcium ions) are available. It is not yet known to what extent individual trapping mechanisms affect long-term storage underground. This aspect is currently being explored in a number of research projects (Bielinski et al. 2008, Zhou et al. 2008, Pruess 2009).

Reservoir simulations can model the behaviour of the underground gas, as shown in Fig. 7-6 (Pruess 2009). Here, the injection is completed after 25 years. At this stage, the injected gas is mainly bound in the supercritical state beneath the cap rock or in the capillary pores (*mobile phase*, upper curve). The *dissolved fraction* (middle curve) also increases continuously throughout the 25 years of storage, but represents only a small percentage of the total CO_2 storage at the end of the storage process. The further course of the dissolution process is unclear – in addition to the modelled course (solid line), a course shown here by the dashed

red line could also be conceivable. The *mineralogical deposit* is only noticeable over the course of millennia, but does increasingly contribute to permanence.

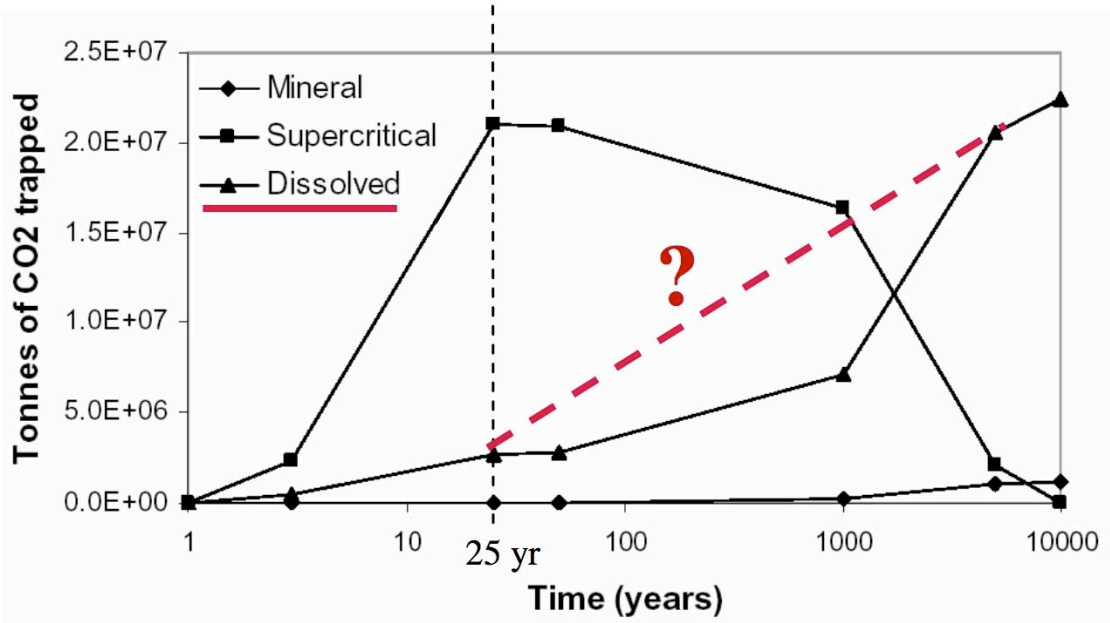


Fig. 7-6 Reservoir simulation of CO_2 injection into a saline aquifer where the injection is stopped after 25 years

Source: Based on Pruess 2009

The storage capacity is calculated on the assumption that the capture process in the power plant, the transport and the storage of CO_2 underground takes place continuously until the storage site is full. Due to the constant injection over a relatively short (geological) period, only the first underground processes are activated. For this reason, capacity estimates generally only include supercritical CO_2. It takes decades before the dissolution and mineral binding takes place in relevant quantities, and these do not affect the estimates. If, however, the storage process is interrupted for a longer period, space may be created for additional injections due to the dissolution of CO_2 in the salt water.

7.4 Methods for estimating capacity

When calculating storage potentials, a methodological distinction is made between a “top-down” and a “bottom-up” approach. In the “top-down” approach, a total volume (for example, for the whole of Germany) is assumed. This total volume is then restricted according to various criteria (“volumetric concept”). Using the “bottom-up” method, single structures are considered and their capacities added together to calculate the total storage potential. While the volumetric concept is usually used for aquifers, the “bottom-up” approach is generally applied for hydrocarbon fields. We will now proceed to review these two concepts in detail.

7.4.1 Deep saline aquifers

The most common method for estimating the capacity of deep saline aquifers is based on the volumetric concept. In this case, the storage capacity is calculated using Formula 7.1:

$$m_{CO_2,theoretical} = V_b \cdot n/g \cdot \phi \cdot traps\% \cdot \rho_{CO_2} \quad (7.1)$$

where

m_{CO_2}	= gravimetric storage capacity, theoretical or effective, [m_{CO_2}] = kg;
V_b	= volume of the potential formation, [V_b] = m^3;
ϕ	= porosity, [ϕ] = %;
n/g	= proportion of sediment structures with porosity and permeability suitable for absorbing CO_2 (net-to-gross ratio), [n/g] = per cent;
$traps\%$	= proportion of traps in the total volume, [$traps\%$] = %;
ρ_{CO_2}	= density of the CO_2, [ρ_{CO_2}] = kg/m^3.

First, the volume (m^3) is calculated from the average available subterranean area (m^2) and the thickness of the aquifers (m). This volume is then restricted to the fraction of the volume that can absorb CO_2, using the net-to-gross ratio. For acceptance reasons and for easier monitoring, CO_2 should only be stored in closed structures. This is documented in most studies, and is achieved by considering *traps%*. The gravimetric theoretical storage capacity $m_{CO_2,theoretical}$ of CO_2 is obtained by taking into account the density ρ_{CO_2}.

The theoretical storage capacity calculated using Equation 7.1 is applied to calculate the pore volume of a reservoir rock. However, it is impossible to fill this total volume with CO_2 because the pores are water-saturated. For this reason, efficiency factor E, which takes the potential water displacement and compressibility into account, is required. Applying this factor produces the effective CO_2 storage capacity (= volumetric capacity in May 2009):

$$m_{CO_2,effective} = m_{CO_2,theoretical} \cdot E \quad (7.2)$$

where

E	= efficiency factor, [E] = %.

To classify the various terms related to capacity, the Carbon Sequestration Leadership Forum (CSLF) proposed the "*techno-economic resource pyramid for capacity for CO_2 geological storage*" (Bachu et al. 2007). A modified version of this pyramid is shown in Fig. 7-7. Factor *E* is used to convert theoretical capacity into effective capacity, which equates to one step higher up the pyramid. This factor *E* is the major unknown quantity in most publications and varies considerably (40 per cent in May et al. 2005, 5–40 per cent in Christensen 2009, 1–4 per cent in Frailey 2008, 0.1–1 per cent in Ehlig-Economides and Economides 2010). A comprehensive list of efficiency factors from various studies is given in (Höller 2009). The efficiency factor does not always relate to the same volume, however, but depends on whether only the traps or the total aquifer is selected as the affected pore volume. If the factor applies to the *total* aquifer, the value *traps%* must be omitted in Formula 7.1.

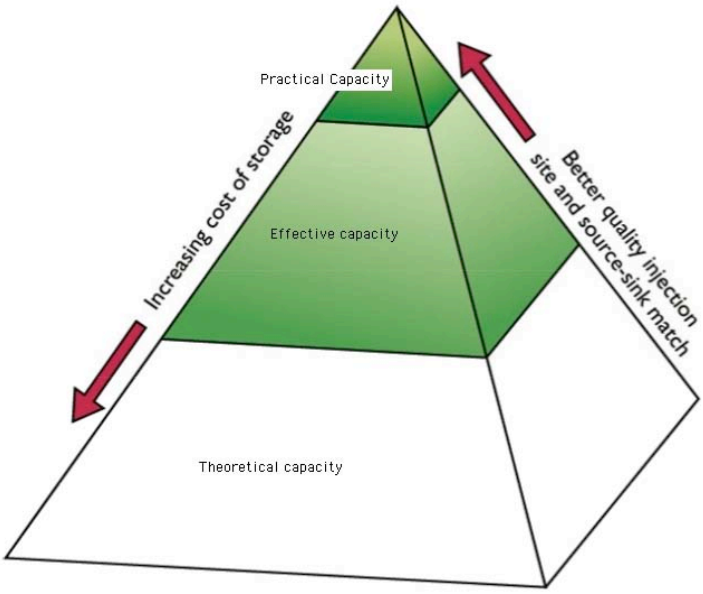


Fig. 7-7 Pyramid showing the interrelation of storage capacities

Source: Modified from Vangkilde-Pedersen et al. 2008

While the efficiency factor is taken to be a fixed amount in most cases, the following two examples show a more detailed breakdown. In both variants, the factor refers to the volume of the *total* aquifer or the affected pore space in the aquifer.

- For *open systems,* the U.S. Department of Energy (U.S. DoE) provides a clear derivation of the efficiency factor. Here *E,* as shown in Equation 7.3, is divided into various partial factors (Frailey 2008). Multiplying these partial factors yields a storage efficiency of 1 to 4 per cent. The net-to-gross ratio (*n/g*), the volumetric efficiency (E_v) and the displacement efficiency (E_d) are taken into account (Höller 2009, simplified following Frailey 2008):

$$E = n/g \cdot E_V \cdot E_d \tag{7.3}$$

- On the other hand, Van der Meer and Yavuz (2009) assume that every system must be viewed as finite, i.e. *closed,* and that it is impossible to displace salt water from the aquifer system. The injected gas only displaces water within the system, i.e. from the trap structure to the adjacent aquifer, but not beyond it. At the same time, however, the reservoir pressure of the total system increases. The space affected by this pressure propagation is called the "total affected space". The arguments presented frequently fail to consider what would happen to the potentially displaced water, because it would occupy space in another area underground or, in the worst case scenario, could reach the earth's surface. For this reason, scientists calculate the estimate using an efficiency factor based on the compressibility of formation water (c_w) and the pores or the rock (c_p). They also take into consideration a maximum possible increase in pressure in the *total* formation (Δp) (compare also Thibeau 2009):

$$E = (c_p + c_w) \cdot \Delta p \tag{7.4}$$

  This factor is applied to the total affected system. In the trap structure where the injection takes place, however, a considerably higher proportion of water could be displaced, as

long as the total pressure does not exceed the maximum. The stability of the limiting cap rock should always be guaranteed, otherwise safety could be jeopardised.

It becomes evident that the aforementioned distinction between *open* and *closed* systems (Fig. 7-5) is crucial to the calculation of the efficiency factor. The more further restrictive factors are considered, the more they decrease the potential for CO_2 injection. The step from *effective* to *practical capacity* is accompanied by economic and regulatory or legal barriers. Geotechnical considerations must also be taken into account. These factors may reduce the potential yet further, due to the quality of the cap, interaction between various storage sites and injectivity per time unit. Competitive usage and public acceptance also play a decisive role (SRU 2009a). If the injection of CO_2 at a particular storage site is rejected by the public, then its practical capacity equals zero.

7.4.2 Depleted oil and natural gas storage sites

The storage capacity for CO_2 in depleted oil and natural gas traps is calculated using the volumes of recovered hydrocarbons. The volume can be calculated from either the originally available reserves and an extraction factor or from the cumulated extraction volume $V_{gas}(STP)$. If a field has not yet been completely exhausted, many authors include an additional proportion of the remaining reserves in the calculation because this space can also be used as a CO_2 storage site once extraction has been completed (Hoth et al. 2007). The calculation is then carried out with a larger volume, leading correspondingly to a higher CO_2 storage potential.

Another factor is required to assess this storage site to allow for the change in density of the oil or natural gas between the reservoir conditions and the earth's surface. This factor is called the *gas expansion factor* (B_g) in the case of natural gas and the *formation volume factor* (FVF) in the case of oil. With the density of CO_2 (ρ_{CO_2}), this produces the calculation in accordance with Formula 7.5 for the theoretical storage quantity of CO_2 in natural gas fields (oil calculations are carried out analogously, but would make only a negligible contribution to the amount of CO_2 storage available in Germany):

$$m_{CO_2} = V_{gas}(STP) \cdot \rho_{CO_2} \cdot B_g \tag{7.5}$$

where

m_{CO_2}	= theoretical gravimetric storage capacity in natural gas fields, [m_{CO_2}] = kg;
$V_{gas}(STP)$	= volume of the extracted natural gas at the earth's surface under standard conditions (p = 1000 hPa, T = 15°C), [$V_{gas}(STP)$] = m^3;
ρ_{CO_2}	= density of the CO_2, [ρ_{CO_2}] = kg/m^3;
B_g	= gas expansion factor, [B_g] = 1.

Most authors do not differentiate between these computed theoretical storage capacities and the effective storage capacity based on an efficiency factor. In the advanced concept in the GeoCapacity report (Vangkilde-Pedersen et al. 2009a), the injected gas or injected water is at least subtracted from the volume introduced for additional recovery.

In 2007, the CSLF defined an efficiency factor for natural gas fields (Bachu et al. 2007). Efficiency factor *E* comprises here of mobility and the buoyancy of the CO_2 underground, the heterogeneity of the geological structures, water saturation and the formation thickness. Thus it contains water migration in a depleted storage site connected to the ground water, which is often observed. The reduction of the pore space due to settlement induced by extraction should also be considered.

Holloway et al. (2006) consider that between 65 and 90 per cent is a realistic efficiency factor. Hendriks et al. (2004) estimate a value of 75 per cent, which would reduce the storage capacity by a quarter. This approach is supported by a new study by the IEA Greenhouse Gas R&D Programme (IEA GHG 2009a). This has led to the downward adjustment of earlier global storage potential estimates. In addition, capacities are also adjusted further downward since 50 and 100 million tonnes of CO_2 are deemed to be the minimum capacity per storage site for onshore and offshore storage, respectively. The Scottish Carbon Capture and Storage Centre also assumes a minimum size of 50 million tonnes of CO_2, but only refers to fields in the North Sea (SCCS 2009b).

7.5 CO_2 storage capacity for Germany

The total capacity for the geological storage of CO_2 is calculated from the capacity estimates for the individual types of formation. For Germany, these types are saline aquifers beneath the landmass, suitable offshore formations (i.e. beneath the North Sea within German sovereign territory) and depleted oil and natural gas storages sites. We will now discuss these types of formation individually. We will then proceed to determine their potential for CO_2 storage, and compare it to other estimates.

7.5.1 The geological situation in Germany

In Germany, most potential storage structures can be found in the North German Basin and the North Sea (Fig. 7-8), where there is a considerable quantity of depleted natural gas fields. These fields would make the rapid introduction of CO_2 storage easier, due to relevant geological data being already available.

Since this storage space is limited, it would be necessary to revert to saline aquifers if CCS technology were to be used on a large scale. These structures can also be found in the North German Basin. The North Sea could serve as potential storage space. It is particularly suitable as it has enormous sediment backfilling (primarily Rotliegendes) that has accumulated from contributory rivers over millions of years. However, the German section is small compared to the possibilities available in Norwegian or British waters. In addition, public acceptance is more likely to be gained for offshore projects than on populated land. Several protest groups across Europe have already campaigned against underground exploration projects and the potential final disposal of CO_2.

Molasse from the northern pre-Alpine area and the Upper Rhine Graben provides a few useful sedimentary structures. Due to seismic activity there, however, the risks involved in using them for CO_2 storage cannot be estimated. For this reason, they should not be included in the calculation.

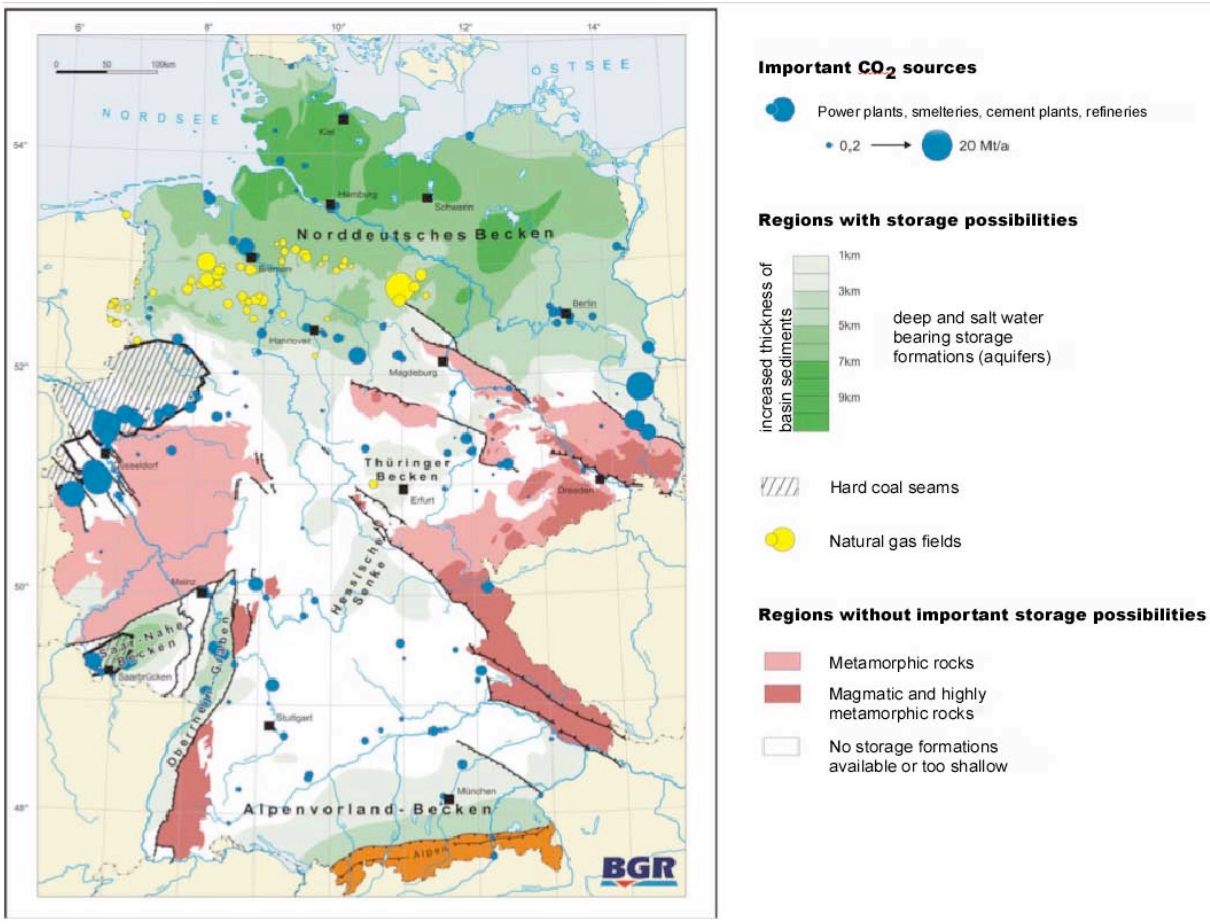


Fig. 7-8 The geographical distribution of CO_2 point sources (power plants and industry) and storage potentials in Germany

Source: BGR

7.5.2 Estimate of the CO_2 storage capacity in saline aquifers beneath German mainland

Values must be added to Equations 7.1, 7.2 and 7.5 from Section 7.4 to be able to estimate a CO_2 storage capacity for Germany. Tab. 7-2 provides an overview of the values used in a number of publications to estimate capacities in saline aquifers (onshore). These values are efficiency factor *E*, the density of the CO_2 ρ_{CO_2}, porosity ϕ, the proportion of traps (*traps%*) and the net-to-gross ratio *n/g*.

These assumptions are compared with our own estimate, which is a conservative approach that endeavours to select cautious values. The factors used will now be briefly discussed:

- In most estimates, *porosity* ϕ is set at 20 per cent, which is why our "own estimate" also includes this figure.
- The proportion of traps (*traps%*) ranges between 3 and 5 per cent, depending on the source. Our own calculation is based on the method by (van der Meer and Egberts 2008). This method relates the efficiency factor to the *total* pore volume affected by the increase in pressure caused by the injection into the trap structure ("total affected space"). For this reason, the proportion of traps is not required for the calculation.

Tab. 7-2 Estimated values by various authors to determine storage capacity in saline aquifers for Germany (onshore)

Author	E	ρ	φ	Proportion of traps	n/g
	%	kg/m³	%	%	%
JOULE II (van der Straaten et al. 1996)	4	700	20.5	3	–
Turkovic (2002)	20	600–635	10–20	5	5–100
May et al. (2005)	40	700	20	2–8	–
Dose (2008)	0.1–0.65 *)	+	20	3–5	–
Meyer et al. (2008)	6–40	600	20	+	–
GeoCapacity (Vangkilde-Pedersen 2009a) "first estimate"	20	700	+	+	25
GeoCapacity (Vangkilde-Pedersen 2009a) "conservative estimate"	5–20	550–700	+	+	25
Own estimate	0.1 *)	600	20	4	100
Own estimate, variants	0.045 / 1 *)	600	20	4	100

n/g = net-to-gross ratio; '–' = not considered; '+' = considered, but no value given

*) relating to the total volume

Source: Höller 2009, extended

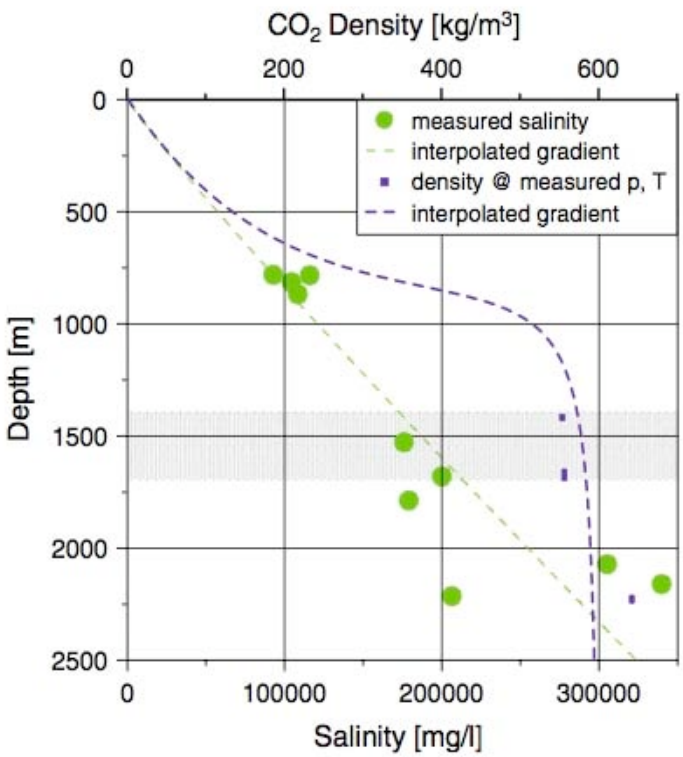


Fig. 7-9 How the CO_2 density and water salinity change with depth

Source: Meyer et al. 2008

- The data for the net-to-gross ratio *n/g* are often unclear, and it is hard to determine whether this factor is in fact included in the capacity calculation. For this reason, this fac-

tor was not considered in our own estimate (the set value of 100 per cent does not influence the final result).

- The *density* ρ of CO_2 chosen in our own estimate is 600 kg/m^3, which falls in the lower region of the values listed. The choice of this value is attributed to (Gerling 2008), who specifies the density of pure CO_2 at between 600 and 650 kg/m^3. If impurities were included, this value would be further reduced. The value chosen is supported by the density development from the Schweinrich structure (see Fig. 7-9).
- The *efficiency factor* is the most significant parameter. Tab. 7-2 shows a range from 0.1 to 40 per cent, i.e. a variation around a factor of 400. The different values depend not only on whether closed or open systems are considered, but also on the volume to which the estimate refers.

  For our own conservative estimate, it appears justifiable to assume only closed formations for CO_2 injection. For this reason, we follow the definition by (van der Meer and Egberts 2008), which interprets all systems as finite. According to this definition, the maximum pressure increase and the compressibility of rock (c_p) and water (c_w) are responsible for calculating efficiency factor *E* (see Formula 7.4). The efficiency factor is applied to the pore volume of the total system.

  With regard to storage site safety, (van der Meer and Egberts 2008) consider a value of 1 MPa for the increase in pressure to be suitable for northern Europe. (Dose 2008) computes a scenario with 1.3 MPa in a similar manner. The value of 1 MPa is therefore assumed for the conservative estimate. Several authors consider a total compressibility c (= c_p + c_w) of 1*10^{-3}/MPa to be realistic (Dose 2008 and Thibeau 2009, amongst others). *Using Formula 7.4, we calculate an efficiency factor of 0.1 per cent*.

  The factors considered must be measured and calculated individually for each structure, depending on their geological characteristics. For this reason, only an average value or range of fluctuation can be selected for the cautious estimate made here. This is implied by two sensitivity analyses:

  - For Sensitivity *Analysis 1,* the maximum increase in pressure is retained at 1 MPa, and a lower value for total compressibility c is assumed. This factor varies in the literature between 0.45*10^{-3}/MPa (van der Meer 2009), 0.8*10^{-3}/MPa (Zhou et al. 2008) and 1*10^{-3}/MPa (Holloway et al. 2009). To represent a range of possible capacities, the lowest value of 0.45*10^{-3}/MPa is chosen. *This sensitivity analysis leads to an efficiency factor of 0.045 per cent.*
  - In *Sensitivity Analysis 2,* on the other hand, the maximum increase in pressure is varied. Here, we referred to other publications in which an increase in pressure in the total system of 6 MPa (Zhou et al. 2008), 8 MPa (Thibeau 2009) or 10 MPa (Holloway et al. 2009) is considered possible. 10 MPa is used for this sensitivity analysis. The total compressibility remains at 1*10^{-3}/MPa. *These values lead to an efficiency factor of 1 per cent.*

Overall, a range of 0.045–1 per cent is yielded for the efficiency factor, with a basic value of 0.1 per cent.

This range is also confirmed in other studies: a current IEA GHG study on storage efficiencies, for instance, computes an efficiency factor of 0.59 per cent, related to the total volume, for closed systems (IEA GHG 2009). (Ehlig-Economides and Economides 2010) also confirm that no more than 1 per cent of the pore volume, and maybe even up to 100 times less, can be used for storage. This would lead to efficiency factors between 0.01 and 1 per cent.

Let us point out here that the assumption of closed systems does not mean that all systems are closed in nature. Some studies assume mainly open systems, while others assume all systems are closed. Bearing in mind the objective of our study, this assumption is viewed as a scenario that represents a lower limit and presumes, for safety purposes, that salt water should not be displaced.

If the values selected for our own estimate are now inserted into Formulas 7.1 and 7.2, a CO_2 storage capacity for aquifers (onshore) of 0.84 billion tonnes is obtained.

An aquifer area of 140,000 km^2 and an average aquifer thickness of 50 m derived from (May et al. 2005) are selected for our estimate.

If both variants of the efficiency factor (0.045 and 1 per cent) are used, storage capacities of 0.378 and 8.4 billion tonnes of CO_2 are yielded.

Since this capacity estimate is based on the volumetric approach, i.e. no individual structures are taken into consideration, the condition of a minimum size of an individual storage site cannot be taken into account. Our own estimate of 0.84 billion tonnes (0.378–8.4 billion tonnes) must be seen alongside results by other authors amounting to 0.47–42 billion tonnes (see Tab. 7-4). The large variation in the values is largely explained by the very different assumptions regarding the efficiency factor.

7.5.3 Estimate of CO_2 storage capacity in saline aquifers of the German North Sea

Estimates of the storage capacity for CO_2 in aquifers of the German North Sea have only recently been published. The first estimate, presented by (May 2009), produced values of between 4 and 10 billion tonnes. However, the calculation used to gain these values was not published. The GeoCapacity Final Report describes these formations in further detail. In this report, a conservative estimate of storage potential of 2.9 billion tonnes was calculated using the “bottom-up” approach (Vangkilde-Pedersen et al. 2009b). In the calculation, only storage sites with a filling capacity of over 100 million tonnes of CO_2 were included. This explicitly conservative estimate seems to be plausible because site-specific analyses were performed, details of which, however, are not given.

For this reason, we refrain here from conducting our own estimate. Instead, we assume the basic value of 2.9 billion tonnes of CO_2 with a range of fluctuation of 1.88–4.50 billion tonnes of CO_2 (Tab. 7-4).

Offshore storage, however, is very different to onshore storage, as described by (Schrag 2009). The pore water in aquifers below the ocean is similar to seawater. Hence, if this water were to escape into the sea, it would not contaminate drinking water or terrestrial vegetation close to the surface, let alone the local population. Storage beneath the seabed should, therefore, be more likely to gain public acceptance. (Schrag 2009) assumes, however, that

pore water would have to be extracted prior to the injection of CO_2 to ensure that the increase in pressure remains controllable. The potential for CO_2 storage could, therefore, be significantly increased. Whether such a release of brine into the sea really is harmless, as (Schrag 2009) maintains, should be examined in more detailed environmental analyses. Here, local flow conditions and the varying salt contents in aquifer and sea water would have to be taken into account.

7.5.4 Evaluation of CO_2 storage capacity in depleted oil and natural gas fields

The CO_2 storage capacity in *natural gas fields* is calculated using the previous cumulated extraction of the natural gas. Since not all natural gas fields in Germany are depleted, the quantity of natural gas in the reserves is also included in the calculation. This inclusion increases the potential storage volume considerably. Below, we will explore how both calculations are computed in further detail.

Tab. 7-3 CO_2 storage capacities for Germany in natural gas fields

	JOULE II	**GESTCO**	**BGR**	**GeoCapacity**	**Own estimate**	
	1996	*2004*	*2005*	*2009*	Basic value	Variant
Size of gas field	> 10 Mt	> 5 Mt	> 10 Mt	> 5 Mt	> 10 Mt	> 10 Mt
(*)	1.78	1.77	2.13	2.18	1.34[a]	1.61[b]
(+)	2.34	2.23	2.75	2.81	1.62[a]	1.94[b]

All quantities given in gigatonnes of CO_2, unless otherwise stated.

* = based on the cumulative previous recovery of natural gas

+ = additional proportion of reserves

[a] = efficiency factor 75%

[b] = efficiency factor 90%

Source: Authors' design

The difference between the various CO_2 storage capacity estimates is lowest for natural gas fields because all calculations are based on the *cumulative recovery* of natural gas (marked with * in Tab. 7-3). However, stipulating the minimum storage size creates a difference. A differentiation is made of between 5 and 10 million tonnes. This means that a natural gas field must have space for at least 5 and 10 million tonnes of CO_2, respectively, in order to be considered as a storage site. It would not be profitable to construct the necessary infrastructure for fields that are too small. It can be seen from Tab. 7-3, however, that this stipulation makes little difference to the estimates. JOULE II, for instance, calculates very similar values for natural gas fields larger than 10 million tonnes to those yielded in GESTCO for fields larger than 5 million tonnes. This is also the case when comparing BGR (Federal Institute for Geosciences and Natural Resources) with GeoCapacity. In the context of these many uncertain assumptions, this difference can, therefore, be overlooked. However, the effect of the upper limit of 50 and 100 million tonne minimum capacity on storage sites defined by (IEA GHG 2009a and SCCS 2009b) should be examined because it would considerably restrict potential.

The *reserve fraction* in the storage sites is significant and it is important to take this into account. This reserve fraction is the part of the natural gas still remaining in the gas fields and which, according to current knowledge, can be extracted prior to potential CO_2 injection. In Tab. 7-3, this is marked with "+". The proportion of potential CO_2 storage to the total volume already determined for the previous amount extracted is applied to the reserves. This additional proportion is then added to the values marked with "*". If, on the other hand, the calculations of BGR and GeoCapacity are compared, approximately the same values are yielded (2.75 billion tonnes compared to 2.81 billion tonnes). It is not clear, however, why BGR/GeoCapacity have generated capacities 20 per cent higher than JOULE II/GESTCO, regardless of whether or not reserves are considered.

For the purpose of our own estimate, the extraction data of German gas fields were reanalysed (based on LBEG 2008). A slightly lower extraction quantity was yielded than in the comparative studies (for further details, see Höller 2009). In addition, a density of 600 kg/m^3 was used, as chosen to calculate capacities in saline aquifers.

This is the only estimate that includes an efficiency factor below the conventionally assumed value of 100 per cent. The range from 75 per cent to 90 per cent was chosen, which (Holloway et al. 2006) also recommend, because it is highly unlikely that CO_2 will completely fill the pores that previously held natural gas (Hendriks et al. 2004). The approach we have chosen has since been substantiated by the new IEA Report, where an efficiency factor of 75 per cent is introduced (IEA GHG 2009a). A storage capacity in natural gas fields ranging from 1.34 to 1.61 billion tonnes of CO_2 (excluding reserves) or 1.62 to 1.94 billion tonnes of CO_2 (including reserves) is then yielded.

For the summary of the total storage capacities for Germany (Tab. 7-4), the value including reserves was used for gas fields. For our own estimate, therefore, 1.62 billion tonnes of CO_2 was used as the basis and 1.94 billion tonnes of CO_2 as a variant.

The quantity of the storage capacity in German oil fields is irrelevant to CCS projects, and is, therefore, not explored in further detail here.

7.5.5 Estimate of the total CO_2 storage capacity for Germany

If all of the reviewed studies are compared, a wide range of values for CO_2 storage capacities in Germany, ranging from 3 to 44 billion tonnes, is produced (see Tab. 7-4 and Fig. 7-10).

If the *total capacity* is considered, the estimate from the JOULE II Report (van der Straaten et al. 1996) is in the lower range of 3 billion tonnes of CO_2. The European research project GESTCO and various estimates by the BGR, on the other hand, yield higher capacities, ranging from 19 to 41 billion tonnes of CO_2. As explained above, however, these estimates are based on general assumptions for the efficiency factor that are not substantiated in detail. These values also appear in the current Final Report of the GeoCapacity project, which was drawn up on behalf of the German side by the BGR. In that report, however, the conservative lower region of the most formative estimate for Germany by (May et al. 2005) is considered realistic, and the maximum CO_2 storage capacity is estimated to be 17 billion tonnes. An initial estimate by RWE (Asmus and Dose 2008) has not been considered in the compilation since it considers only the area of North-West Germany excluding the North Sea (around 6 billion tonnes of CO_2 when considering fields larger than 10 million tonnes).

Tab. 7-4 CO_2 storage capacities for Germany in various formations

	JOULE II	GESTCO	BGR	GeoCapacity	Own estimate	
Formation	*1996*	*2004*	*2005*	*2009*	Basic value	Variants
Onshore saline aquifers	0.47	23–42	12–28	12	0.84	0.38 / 8.40
North Sea aquifers	?	?	4–10	2.9	2.90	1.88 / 4.50
Gas fields	2.34	2.23	2.75	2.81	1.62	1.62 / 1.94
Oil fields	0.06	0.10	0.11	marginal	negligible	
Total	≈ 3	25–44	19–41	≈ 17	≈ 5	≈ 4 / ≈ 15

All quantities given in gigatonnes of CO_2

The values for gas fields contain reserves.

JOULE II: van der Straaten et al. (1996)

GESTCO: Christensen and Holloway (2004)

BGR: May et al. (2005); May (2009); Gerling (2008b)

GeoCapacity [conservative]: Vangkilde-Pedersen et al. (2009c)

Own estimate:

Onshore aquifers: efficiency factor related to aquifer volume 0.1 per cent (basic value), 0.045 and 1 per cent (variants);

North Sea aquifers: results taken from GeoCapacity.

Source: Based on Höller 2009

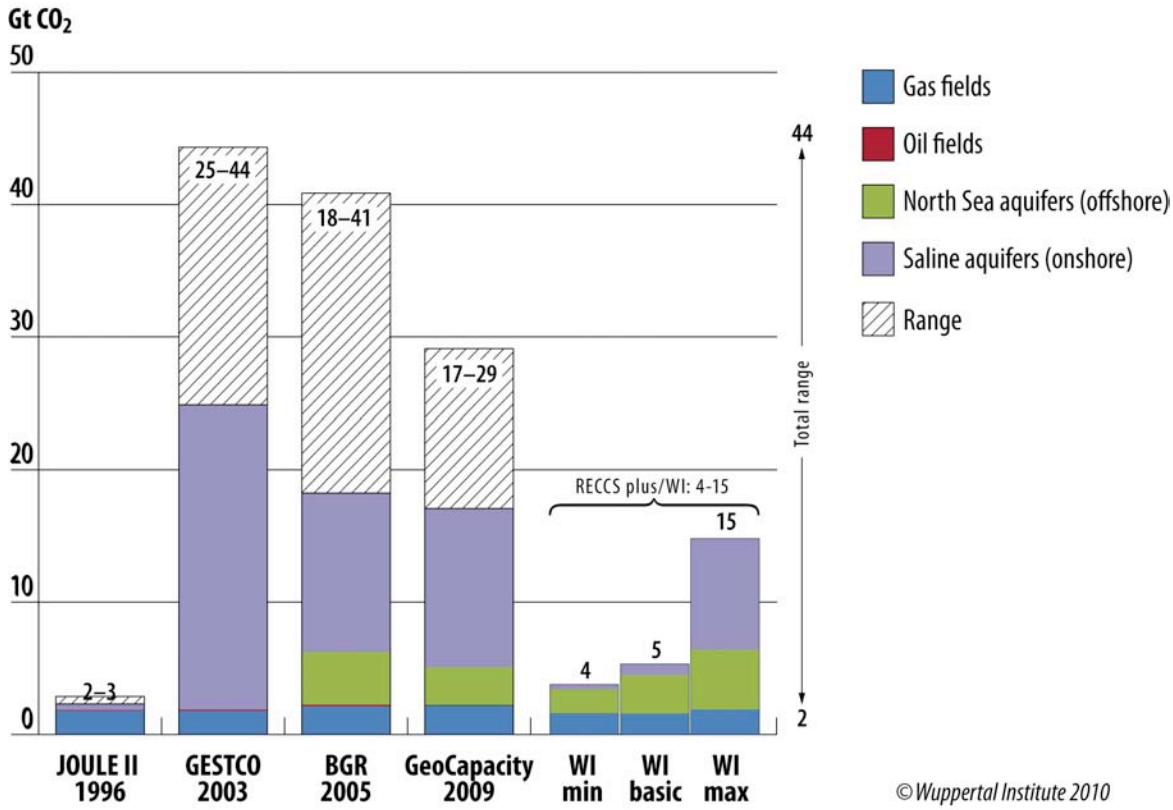


Fig. 7-10 Estimates of CO_2 storage capacity for Germany

Source: Authors' design

Our own cautious estimate amounts to 5 billion tonnes of CO_2 (basic value). The uncertainty fluctuation yields values from 4 to 15 billion tonnes of CO_2.

As a result of the analysis, with the basic value and the lower sensitivity analysis, German offshore capacities are higher than the onshore value, although onshore German aquifers are in principle considerably larger than offshore aquifers. The reason for this is that, due to a lack of reliable data for offshore aquifers, it was not possible to carry out a comparable cautious estimate, as was the case for onshore aquifers. Instead, the conservative estimate from the GeoCapacity Final Report was assumed. If the cautious assumptions are moderated and if, as in the upper sensitivity analysis, a higher increase in pressure is permitted, a different relationship between onshore and offshore emerges.

Apparently, the greatest variation in the different estimates is also in the area of *onshore saline aquifers* (ranging from 0.38 to 42 billion tonnes of CO_2), which suggests that there are considerable uncertainties in the estimates. The conservative estimate with regard to saline aquifers of 12 billion tonnes contained in the GeoCapacity report has since also been adopted by the German government, which estimated its storage potential to be “more in the bottom area of this range” (of 20+/-8 billion tonnes) (BMWi 2009).

7.5.6 Comparison of the calculated storage potential with the quantity of CO_2 emitted in Germany

The estimates of storage capacities only become meaningful if the sources and sinks, i.e. supply and demand for CO_2 storage sites, are compared with one another. This is highlighted using two different CO_2 emissions scenarios:

- The *total* CO_2 emissions caused by large point sources in Germany (power plants and industry)[59] were 388 million tonnes per annum in 2007. If additional energy expenditure for the CCS technology chain of around 30 per cent (116 million tonnes per annum) and a CO_2 capture rate of 90 per cent are assumed, ultimately 454 million tonnes of CO_2 would have to be stored annually. Provided that the total storage volume is available at the beginning of the injection operation and the injection of the complete emissions for one year is possible, the capacity of 17 billion tonnes computed in the GeoCapacity project would suffice for 37 years. If the estimate of 5 billion tonnes presented here is considered, the entire quantity from these point sources could be stored for 12 years.
- If a “realistic” scenario is assumed, as presented for Germany in Chapter 10, a total of 1.2 billion tonnes of CO_2 can be separated in the power plant sector by the year 2050[60]. It has been taken into account that not all emissions from combined heat and power plants located in cities can be separated; in addition, the transportation of CO_2 from power plants and industrial plants in southern Germany (see Fig. 7-8) is likely to be uneconomical, due to the long distances involved. The quantities of CO_2 incurred in this scenario could be stored within Germany, even according to the conservative capacity estimate. There would also be additional space for emissions from industry.

[59] Determined via the European Pollutant Emission Register EPER, enquiry regarding electricity and heat supply (all combustion plants with emissions > 1 million t/a), 2007, www.EPER.de

[60] “REALISTISCH I” scenario for CCS in the power plant sector: new construction of 75 per cent of steam and 40 per cent of combined heat and power plants with CCS; retrofitting of 40 per cent of steam and of 20 per cent of combined heat and power plants; CCS chain commercially operational from the year 2020.

Only the *effective* capacity, however, was used as the basis in each comparison. The *practical* capacity, generally lower than the effective capacity, would yield lower utilisation periods.

7.5.7 Conclusions from the analysis for Germany

The present estimates of the CO_2 storage potential for Germany in saline aquifers and depleted natural gas fields (both onshore and offshore) reveal a wide range of *effective capacity* of between 3 and 44 billion tonnes of CO_2. The average can be taken as 17 billion tonnes of CO_2, which was the conservative estimate published in the GeoCapacity project for Germany. The main reason for this extreme range is that the assumptions of storage efficiency vary considerably.

- Efficiency in saline aquifers, which describes the proportion of water in the saturated subsurface that can be displaced by the injected CO_2, ranges from 0.1 to 40 per cent in the analysed studies. Hence the range of fluctuation of capacities is also enormous – for onshore aquifers alone, previous estimates vary between 0.47 billion tonnes (JOULE II), 12 billion tonnes (GeoCapacity), 28 billion tonnes (BGR) and 42 billion tonnes (GESTCO).
- With natural gas fields, efficiency varies between 75 and 100 per cent of the cumulated recovery of natural gas, and leads to a storage potential in the analysed studies of between 1.7 and 2.8 billion tonnes of CO_2.

There is less deviation in the individual studies with regard to the values chosen for the density of CO_2, the proportion of traps and porosity.

For our *own cautious, conservative estimate*, which seeks to illustrate a lower limit of the potentially available capacity, in keeping with the objective of the study, the following results can be summarised:

- With the deep saline aquifers, it is assumed that CO_2 can only be injected in trap structures. Many authors justify this limitation because of its higher permanence, leading to greater public acceptance. In addition, every system is viewed as being closed, resulting in an efficiency factor, related to the total onshore aquifer volume, of 0.1 per cent. These assumptions are confirmed by several new studies, which take the lower efficiency factors into account and advocate taking only closed underground systems into consideration. Based on these assumptions, the conservative estimate of the storage capacity for Germany in onshore saline aquifers amounts to 0.84 billion tonnes of CO_2. The sensitivity analyses with efficiency factors 0.045 per cent and 1 per cent yield a range of fluctuation from 0.38 to 8.4 billion tonnes of CO_2.
- The offshore aquifers had already been estimated conservatively in the GeoCapacity report, which is why this calculation is assumed here. It gives an average capacity of 2.9 billion tonnes of CO_2 (fluctuation of 1.88 to 4.4 billion tonnes of CO_2). These values are considerably higher than the capacities for onshore aquifers, even though German onshore aquifers are considerably larger than their offshore counterparts. The reason for this is that, due to a lack of reliable data for offshore aquifers, it was impossible to carry out a comparable cautious estimate, as had been the case for onshore aquifers. If the cautious assumptions for onshore aquifers are moderated and if, as in the upper sensi-

tivity analysis, a higher increase in pressure is permitted, a different relationship between onshore and offshore appears.

- A storage potential in depleted natural gas fields ranging from 1.34 to 1.61 billion tonnes of CO_2 (excluding reserves) and 1.62 to 1.94 billion tonnes of CO_2 (including reserves) was calculated by setting an efficiency factor of between 75 and 90 per cent. This assumption seems to be justified because it is highly unlikely that the pores, previously filled with natural gas, would be completely filled with CO_2.
- Taking all formations together, the cautious, conservative estimate for Germany in this study totals 5 billion tonnes of CO_2 as the basic value. The uncertainty fluctuation yields values from 4 to 15 billion tonnes of CO_2.

If the *total* CO_2 emissions caused by large point sources in Germany (power plants and industry) are considered (388 million tonnes per annum in 2007), then ultimately, 454 million tonnes of CO_2 would have to be captured annually. With the conservative estimate, these emissions can be stored for 12 years (basic value) or for 8 or 33 years (sensitivity values). If the “Realistisch I” scenario is assumed, as calculated in Chapter 10 for Germany, a total of 1.2 billion tonnes of CO_2 could be captured in the power plant sector by the year 2050, which, even under the assumption of the lowest estimate, could be stored within the geographic region of Germany. Only the *effective* capacity, however, was used as the basis in each comparison. The *practical* capacity, generally lower than the effective capacity, would yield lower utilisation periods.

Our analysis of the studies and the adoption of a conservative estimate show that there remain major uncertainties concerning the estimation of storage potential, particularly with regard to saline aquifers. A further outcome is that the variation of individual parameters has a considerable impact on the results of the calculation. We should point out that not only existing, but also our own estimates, are based on rough data. It is important to state a lower estimate, however, in the sense of a minimum value, to give politicians and industry a basis for planning legislation and further investments.

Since the storage capacities analysed are merely approximate regional estimates, the parameters chosen should be checked and further research and geological investigations should be undertaken to improve accuracy and knowledge. The objective should be to gain extensive geological knowledge of all potential storage sites. This would subsequently establish the availability of potential storage and, therefore, the volume at sites. Although the Catalogue of Storage Capacities in Germany, currently under development, will help to improve the database, it is by no means adequate with regard to the precise assessment of (site-specific) storage options.

In addition, several geo-technical factors could not be taken into account in this study:

- In the discussion about the total quantity of effective storage capacity, it is often presumed that all emissions from point sources can be injected. Instead of the cumulated storage potential discussed here, however, the possible injection rate is likely to be the limiting factor. (Gerling 2010), for instance, estimates the maximum quantity of CO_2 that can be injected annually into storage sites in Germany, based on assumptions by the BGR, to be 50–75 million tonnes of CO_2. Detailed examinations are required here to determine which CCS potentials should, in fact, be implemented on the time line.

- How neighbouring structures are influenced by the injection of CO_2 (for instance, with regard to pressure) and the effect this has on total capacity are only rarely considered in storage calculations. This *interference* should be examined further in practice, and should be included in the calculations to refine this aspect.
- Underground *seismic activity* continues to be important. Areas that are susceptible to natural earthquakes are precluded as storage sites. In addition, seismicity induced by drilling and CO_2 injection should also be analysed and avoided.

7.6 CO_2 storage capacity in Europe

Following the detailed analysis of the storage options for CO_2 within Germany, this section now turns to the geology of Europe. We will first give an overview of existing studies for the whole of Europe, before describing individual countries or groups of countries in further detail. The analysis centres on Germany, and endeavours to determine whether neighbouring countries have sufficient space for possibly accepting and storing German CO_2 emissions. In particular, the North Sea could serve as a potential storage site, and is explored separately. A closer look is taken at the Utsira formation in the Norwegian North Sea. We will also examine the United Kingdom of Great Britain and Northern Ireland (UK), Norway, Denmark and the Netherlands in more detail.

For each country, capacity estimates for saline aquifers, natural gas and oil fields will be compiled, and a conservative estimate selected. In individual cases, we have added our own analyses to this data. The capacity calculated in this way is not matched, however. If the sources and sinks were scrupulously matched on the basis of potential transport routes, infrastructure considerations and issues of public acceptance, the available storage space would be reduced further.

The results of the conservative estimate will then be compared with emissions from large point sources (power plants and industrial plants) from the country in question (Tab. 7-6). This comparison will enable us to state how much space could potentially be made available for foreign greenhouse gas emissions. Here, the CO_2 emissions from 2007 are used, despite the fact that these figures neither consider the increased consumption of energy required to capture CO_2 nor the capture rate.

For reasons of clarity, the storage options in European countries that are at a greater distance from Germany, and therefore less significant in this context, are only explained briefly.

7.6.1 Overview of existing CO_2 storage estimates for Europe

Europe has a wide range of geological structures. Porous sedimentary deposits, many of which can be found in the North Sea region, are particularly suitable for the storage of CO_2. For this reason, the United Kingdom and Norway have the largest storage capacities. Tab. 7-5 gives an overview of the various estimates that already exist for Europe, by comparing the estimates of the three large European research projects on CO_2 storage capacities: JOULE II (van der Straaten et al. 1996), GESTCO (Christensen and Holloway 2004) and GeoCapacity (Vangkilde-Pedersen et al. 2009). In all, the storage estimates vary between 63 and 800 billion tonnes of CO_2.

Saline aquifers

The range of estimates for saline aquifers is considered to be very wide. Calculations for oil and natural gas fields fluctuate much less because better data sets are available for these formations. JOULE II assumes a wide range for saline aquifers from 30 to 773 billion tonnes of CO_2. GESTCO adopts 71 to 116 billion tonnes of CO_2 for Europe. ECOFYS (Hendriks et al. 2004), on the other hand, is more cautious, and describes 10 billion tonnes as its "best estimate" for saline aquifers from a range of 1 to 47 billion tonnes. GeoCapacity also includes the North Sea, and therefore obtains a higher capacity of 100 to 350 billion tonnes of CO_2.

Oil fields

With regard to the oil fields of Europe, storage capacities range from 6 billion tonnes of CO_2 (JOULE II) to 16 billion tonnes of CO_2 (ECOFYS). Many of these fields are in the North Sea, and attempts are being made to increase recovery using CO_2 injection. This process, called "enhanced oil recovery", will be described separately for Norway and the UK in Section 7.8.2.

Natural gas fields

Global estimates of the CO_2 storage potential in depleted natural gas fields are being dramatically revised downwards since the publication of a study conducted by the IEA Greenhouse Gas R&D Programme (IEA GHG 2009a). Formula 7.5, described in Section 7.4.2, is used to calculate the effective capacity in the top-down approach, by applying an efficiency factor of 75 per cent. With regard to this factor, (Pershad and Slater 2007) differentiate between whether water enters a gas field ("water drive") or whether conditions prevail under which it is emptied rapidly ("depletion drive"). If water enters the field, the efficiency factor for the calculation is reduced to 65 per cent. If, on the other hand, "depletion drive" prevails, a 90 per cent replacement of the recovered natural gas is assumed. In uncertain cases, 65 per cent is also applied.

Tab. 7-5 CO_2 storage capacities in Europe (known estimates)

Formations		**JOULE II**	**GESTCO**	**ECOFYS**	**GeoCapacity**	**IEA GHG**
	Year	1996	2004	2004	2009	2009
Saline aquifers		30–773	71–116	10	100–350[a]	-
Oil fields		6	6.8	15.9	25–30	-
Natural gas fields		27	30.2	58.8		37–62[b]
Coal fields		-	0.6–1.2	12.1	1–1.5	-
Total		63–806	109–154	96.8	126–381.5	

All quantities given in gigatonnes of CO_2, unless otherwise stated.

ECOFYS's "best estimate"; JOULE II ranges between conservative assumptions and theoretical capacity; GeoCapacity ranges between conservative and effective estimate

– = not specified

[a] = including the North Sea

[b] = effective capacity = 62 gigatonnes of CO_2, practical capacity = 37 gigatonnes of CO_2, matched capacity = 11 gigatonnes of CO_2

Source: Authors' design

(IEA GHG 2009a) also calculates a *practical* capacity, based on the minimum size of a field. According to this study, an onshore field must be able to hold at least 50 million tonnes of

CO_2, while 100 million tonnes is required as the minimum size offshore. This requirement reduces the potential by around 40 per cent. In addition, 1 per cent of the fields is excluded to take into account potential cases of leakage.

On a European scale, a theoretical CO_2 storage capacity in natural gas fields of 83 billion tonnes is yielded. The effective capacity is 62 billion tonnes, and the practical capacity averages 37 billion tonnes of CO_2 (IEA GHG 2009a). If the sources are now matched with sinks (practical capacity), only 11 billion tonnes can be used in depleted natural gas fields in western Europe to store CO_2 up to 2050. Furthermore, the majority of these gas fields are located in the North Sea.

In comparison, ECOFYS (Hendriks et al. 2004) gives a “best estimate” of 59 billion tonnes of CO_2, which corresponds to the effective capacity. Higher estimates are given by Scottish researchers (Haszeldine 2009b), who suggest 150 billion tonnes of CO_2 for hydrocarbon fields alone in the region of the United Kingdom (see Section 7.6.3). JOULE II, GESTCO and the GeoCapacity report, on the other hand, provide lower values of between 25 and 30 billion tonnes of CO_2 for natural gas fields.

Coal fields

Very little research has been carried out into the injection of CO_2 into coal fields. The potential quantity of CO_2 that could be stored in these structures appears to be very limited (estimates range from 0 to 12 billion tonnes of CO_2 for Europe). Due to the uncertainties and the estimated low potential, there is no further consideration of these storage sites in this study.

Tab. 7-6 European estimates of CO_2 storage capacities and emissions from point sources in all European countries

	JOULE II						GESTCO			GeoCapacity			
Year	1996						2004			2009			
Formation	Aquifers		Oil fields		Gas fields		Deep saline aquifers	Hydrocarbon fields	Coal fields	Deep saline aquifers	Hydrocarbon fields	Coal fields	*Emissions from large point sources*+
	Onshore	Offshore	Onshore	Offshore	Onshore	Offshore							
Unit	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Gt CO_2	Mt CO_2/a
Country													
Albania										0.02	0.11	-	*0*
Belgium	0	0	0	0	0	0	0.10	-	0.43	0.20	-	-	*58*
Bosnia-Herzegovina										0.20	-	-	*9*
Bulgaria										2.10	0.00	0.02	*42*
Croatia										2.71	0.19	-	*5*
Czech Republic										0.77	0.03	0.05	*78*
Denmark	47	?	0	0.13	0	0.46	16.00	0.63	-	2.55	0.20	-	*28*
Estonia										-	-	-	*12*
France	3	?	0.05	0	0.88	0	0.6-26	0.00	-	7.92	0.77	-	*131*
FYROM										0.39	-	-	*4*
Germany	2	?	0.06	0	2.34	0	23-43	2.33	-	14.90	2.18	-	*465*
Greece	?	?	0	0.01	0	0.02	2.20	0.02	-	0.18	0.07	-	*69*
Hungary										0.14	0.39	0.09	*23*
Ireland	0	?	0	0	0	0.16							
Italy	0.353	0.084	0.04	0.07	0.85	0.84				4.67	1.81	0.07	*140*
Latvia										0.40	-	-	*2*
Lithuania										0.03	0.01	-	*6*
Luxemburg	0	0	0	0	0	0				-	-	-	-
The Netherlands	5	?	0.03	0	8.46	0.82	1.60	10.96	0.17-0.85	0.34	1.70	0.30	*92*
Norway	0	476	0	3.1	0	7.19	12.86	12.60	-	26.03	3.16	-	*28*
Poland										1.76	0.76	0.42	*188*
Portugal	0	?	0	0	0	0							
Romania										7.50	1.50	-	*67*
Slovakia										1.72	-	-	*23*
Slovenia										0.09	0.00	-	*7*
Spain	?	?	0	0.01	0	0.04				14.00	0.03	0.15	*158*
United Kingdom	0	240	0.04	2.62	0	4.88	14.70	10.46	-	7.10	7.30	-	*258*
Total per structure	57.35	716.08	0.22	5.94	12.53	14.41	71,20-116,60	36.99	0.60-1,28	95.72	20.22	1.09	*1,893*
Total	**807***						**109-155**			**117**			
* = Conservative estimate for saline aquifers in total 63 Gt CO_2.													
+ =Emissions from large point sources (power plants and industry) calculated without additional usage from CO_2 capture processes (20-40% higher emissions)													

Source: Authors' design, using the European studies JOULE II from (van der Straaten et al. 1996); GESTCO from (Christensen et al. 2004); GeoCapacity from (Vangkilde-Pedersen et al. 2009a).

7.6.2 Important neighbouring countries for Germany regarding CO_2 storage

If German storage sites are insufficient for storing the country's captured CO_2, a European solution with regard to transport and storage could help. Germany's direct neighbours – Poland and the Czech Republic to the east, the Netherlands and France to the west and Denmark to the north – could then accept potential CO_2 emissions and store them underground. Due to their geological activity, the Alpine states south of Germany are unsuitable. The neighbours to the north who have storage potential in the North Sea – Norway and the UK – will be considered in detail in Section 7.6.3. Whether or not the cross-border transportation of CO_2 will take place depends mainly on the storage capacity and emissions caused in the respective country. For this to happen, clear political resolve and strong financial incentives would be required (Haszeldine 2009a).

The other European states are too far away from German power plants. From today's perspective, therefore, they can be excluded from being possible candidates for a CO_2 transfer. Average distances ranging from 200 to 500 km are usually assumed; beyond this distance, transport costs increase considerably (UBA 2006). If the price of CO_2, emissions trading or other variables (such as the use of CO_2 to enhance oil recovery) were to change, however, the currently prohibitive factor of distance could also change.

The Netherlands

The older studies in JOULE II (1996) and GESTCO (2004) assume high CO_2 storage capacities in *saline aquifers* in the Netherlands of 1 to 5 billion tonnes of CO_2. According to the latest findings, estimates are lower, ranging from 340 million tonnes (GeoCapacity) to 750 million tonnes of CO_2 (Faaij et al. 2009) (Tab. 7-7). Similar efficiency factors of 2 to 6 per cent are applied. If stated, the density of CO_2 is assumed to be 700 kg/m^3. The structures identified are very small; none are able to store more than 50 million tonnes of CO_2. For this reason, (Faaij et al. 2009) set a minimum size of 5 million tonnes for trap structures. If, on the other hand, 50 million tonnes of CO_2 is defined as the minimum storage size, all aquifers would be excluded.

Tab. 7-7 Comparison of CO_2 storage capacities in the Netherlands

Formation		**JOULE II**	**GESTCO**	**GeoCapacity**	**v.d. Broek et al.**	**Faaij et al.**
	Year	*1996*	*2004*	*2009*	*2009*	*2009*
Aquifers		1–5	1.6	0.34	0.4	0.75 [b]
	Efficiency factor (%)	*4*	*2–6*	*2–6*	-	*2*
	Density of CO_2 (kg/m^3)	*700*	*700*	*700*	-	-
Oil fields		0.03	10.96 [a]	1.7	2.7	0.04
Gas fields		*9.28* [a]				2.75
Total		10.31–14.31 [a]	12.56 [a]	2.04	3.1	3.54

All quantities given in gigatonnes of CO_2, unless otherwise stated.

– = not specified

[a] = including Groningen gas field, with 7.4 gigatonnes of CO_2.

[b] = structures > 5 million tonnes of CO_2; with a minimum size of > 50 million tonnes, no storage capacity in aquifers

Source: Authors' design

As a large producer of natural gas, the Netherlands has the largest storage capacities in *depleted natural gas fields*. Depending on the estimate, they range from 1.7 to over 10 billion tonnes of CO_2. In the estimates, the efficiency of the replacement of recovered gas by CO_2 is assumed to be 100 per cent. Since many of these fields are still in operation, however, the capacity should be given from a certain point in time. The greatest potential is offered by Groningen gas field, which has storage space for over 7 billion tonnes of CO_2. The latest evidence suggests that this field will only be depleted sometime between 2040 and 2050, and cannot be used for the injection of CO_2 beforehand (Faaij et al. 2009).

The potential for CO_2 injection in *oil fields* is very low. The largest oil field would not be able to store more than 34 million tonnes of CO_2, and all other oil fields are excluded as potential storage sites (JOULE II).

The three estimates for the *total CO_2 storage* in the Netherlands from 2009 (GeoCapacity, van den Broek et al. 2009, Faaij et al. 2009) range from between 2 and 3.5 billion tonnes of CO_2, which is considerably lower than earlier estimates (JOULE II at 14.31 billion tonnes of CO_2 and GESTCO at 12.56 billion tonnes of CO_2) which, however, include Groningen gas field (7.35 billion tonnes), amongst others (Tab. 7-7).

Summarising, a capacity of around 3 billion tonnes of CO_2 is used as a conservative estimate that meets the criteria set in this report.

The time dependence of the storage potential in natural gas fields is important for the Netherlands, because only a small amount of space would be available in the short term (around 1 to 2 billion tonnes of CO_2 storage potential in 2020 (Faaij et al. 2009, Schreurs 2008)). According to (Schreurs 2008), this potential will increase by 2025 to around 2.2 billion tonnes of CO_2, because only a few gas fields will be completely depleted by then.

For domestic *emissions from large point sources,* amounting to 92 million tonnes of CO_2/a (GeoCapacity), however, this capacity would suffice at first sight (see Tab. 7-6).

There could, however, also be a conflict in the Netherlands over the storage of natural gas. If the country's role as the hub for European gas supply is to be further extended, potential for the underground storage of natural gas could be reduced, because this appears to be more commercially attractive than the storage of CO_2 (Faaij et al. 2009). It is also debatable whether the aquifers are at all suitable for storage. If storage sizes of 100 million tonnes are required to place emissions from a large power plant into one single storage site for its entire service life, the storage potential in the Netherlands would be zero. On the other hand, storage sites with smaller capacity could be used if they were in the immediate vicinity of small power plants or industrial plants.

Due to the long wait for several inland storage structures and the possible competition with natural gas storage, the large storage potential in the UK waters of the southern North Sea and in the Norwegian Utsira formation are being considered for the potential construction of CCS infrastructure (van den Broek et al. 2009). To achieve this, a large pipeline project would have to be initiated (see Section 7.6.3).

For the *largest point sources in Germany,* located in North Rhine-Westphalia, transporting CO_2 to the Netherlands and further on towards the North Sea would therefore be a potential way of reducing CO_2. However, Germany would have to assess whether this disposal route

would be economically prudent, because the Netherlands would also charge transmission fees, which would have to be offset against the costs for its own infrastructure (van den Broek et al. 2009).

France

A third of France is underlaid with deep sediments, which are subdivided into various basins, the largest being the Paris Basin to the north of the country. Triassic and Jurassic deposits have filled these basins. There are other large sedimentary covers in the Aquitaine Basin in the south-west, in the Rhone Basin and in the Alsace Basin.

JOULE II calculated that the *saline aquifers* would be able to store 1.5 billion tonnes of CO_2. GESTCO generated a CO_2 storage capacity of 670 million tonnes in trap structures of saline aquifers (without considering the proportion of traps, the unrealistically high figure of 26 billion tonnes of CO_2 was computed). GeoCapacity was less optimistic, obtaining a capacity in suitable aquifers of around 8 billion tonnes of CO_2, without the limitation to traps. With a 3 per cent proportion of traps, this value would decrease to 0.24 billion tonnes of CO_2.

All *French gas and oil fields* are onshore: gas is mainly located in the Aquitiane region, and oil in the Paris Basin. According to JOULE II estimates, the storage capacity in these hydrocarbon reservoirs is under 1 billion tonnes of CO_2 (50 million tonnes in oil fields and 880 million tonnes in gas fields). GESTCO, however, does not envisage any scope for storage in hydrocarbon fields. According to GeoCapacity, on the other hand, 770 million tonnes of CO_2 could be stored in depleted oil and gas fields, which roughly corresponds with the JOULE II value.

In total, the storage capacity for France is given as 0.6 to 26 billion tonnes of CO_2 (GESTCO). It is more realistic to assume, however, that the potential will not exceed 1 billion tonnes of CO_2 (GeoCapacity).

The figure stated in GeoCapacity of 1 billion tonnes of CO_2 is therefore selected as the conservative estimate.

Since France is committed to nuclear power, only low *CO_2 emissions from large point sources* are observed. In 2008, they amounted to 130 million tonnes of CO_2/a (see Tab. 7-6). The storage space generated for France, however, does not offer any long-term prospect for CCS in France. With a capacity of 1 billion tonnes, emissions of 130 million tonnes of CO_2 per annum could only be stored for 7 years. Increased emissions as a result of the additional consumption for CO_2 capture would be added to this amount, creating an even shorter time span. Thus there is no space in French underground formations for *German emissions*.

Poland and the Czech Republic

If there was suitable storage potential in Poland and the Czech Republic, emissions in the German province of Lusatia, especially from lignite-fired power plants, could be transported over shorter distances to the east than to the storage sites of Schleswig-Holstein or the North Sea. In the GeoCapacity report, these countries were investigated for the first time with regard to their capacities for storing CO_2.

For Poland, a potential of 1.76 billion tonnes of CO_2 in *aquifers* and 0.76 billion tonnes of CO_2 in *hydrocarbon fields* was generated. In addition, there is estimated to be 415 million tonnes

of CO_2 storage space in coal fields. The most promising sediment basin is located in the Polish Lowlands.

Although there is a lack of comparable studies, around 3 billion tonnes of CO_2 is selected as the conservative estimate.

With *Polish CO_2 emissions* amounting to 188 million tonnes per annum (see Tab. 7-5), this space would be required for national plans, since the Polish government would like to advance CCS technology, and strongly promotes it.

The Czech Republic offers much lower capacities, totalling 850 million tonnes of CO_2, against their own CO_2 emissions of 78 million tonnes per annum.

Due to low capacities and national requirements, especially in the case of Poland, the option of an eastward *CO_2 transfer from Germany* appears to be more or less inconceivable.

Denmark

As Germany's northern neighbour, structures in Denmark could act as potential storage sites for CO_2 (Tab. 7-8). Most of the potential *aquifer structures* are located onshore in the Danish Basin, where Permian sediments with thicknesses of up to 9,000 m exist. In Denmark, it is assumed that storage would only be possible in trap structures. It is anticipated that any other option for storing CO_2 would meet with public opposition. According to JOULE II, their potential amounts to 5.6 billion tonnes of CO_2 (calculated using an efficiency factor of 6 per cent). If storage was not restricted to traps, there would be a potential of 47 billion tonnes of CO_2.

A variety of assumptions were defined for GESTCO and applied to the selection of suitable structures. In addition to having a suitable depth (900–2,500 m) and size (larger than 100 million tonnes of CO_2 theoretical capacity), the structures must, above all, have a safe cap rock, and the formation must not be fractured. When these criteria are applied, there remains a collection of only 11 large structures that can be considered for the storage of CO_2. Using measured and extrapolated values, the theoretical capacities of each formation was computed. With an efficiency factor of 40 per cent for open aquifer systems, a total capacity of at least 16 billion tonnes of CO_2 was calculated.

Tab. 7-8 Comparison of CO_2 storage capacities in Denmark

Formation		**JOULE II**	**GESTCO**	**GeoCapacity**
	Year	*1996*	*2004*	*2009*
Aquifers		5.6–47	16[a]	0.7[b]–2.5
	Efficiency factor (%)	6	40	6
	Approach	Top-down	Bottom-up	
	Density of CO_2 (kg/m^3)	700	630	630
Oil fields		0.13	0.628	0.203
Gas fields		0.46		
Total		6.2–47.6	16.6	0.9[b]–2.7

All quantities given in gigatonnes of CO_2, unless otherwise stated.
[a] = only fields > 100 million tonnes theoretical capacity
[b] = only fields > 100 million tonnes effective capacity

Source: Authors' design

Based on this capacity (16.7 billion tonnes of CO_2), a conservative estimate is given in the GeoCapacity Final Report on the basis of efficiency factors for closed systems (0.1 to 12.2 per cent are calculated). Based on an efficiency factor of 6 per cent, 2.5 billion tonnes of CO_2 is presented as a realistic figure.

Within this effective potential, only four structures are large enough to store more than 100 million tonnes of CO_2, reducing the capacity to 2.3 billion tonnes. The Thisted formation alone comprises over 72 per cent of this capacity. This could lead to difficulties because GESTCO has shown a very low degree of permeability for this structure (< 2 mD), which would make injections hard, or even impossible. For this reason, the Thisted structure is excluded from the conservative estimate, resulting in an effective potential for CO_2 storage in saline aquifers in Denmark of 700 million tonnes.

The *oil and gas fields* of the Danish North Sea offer virtually no significant capacities: estimates vary between 203 million tonnes (GeoCapacity), 590 million tonnes (JOULE II) and 628 million tonnes of CO_2 (GESTCO). The complete replacement of the hydrocarbons by CO_2 was assumed in each case. The GeoCapacity value was taken to be the conservative estimate.

In summary, a capacity of around 1 billion tonnes of CO_2 is used as the conservative estimate.

A comparison with the *annual emissions* in Denmark from point sources (28 million tonnes of CO_2 in 2007, see Tab. 7-5) shows that emissions could be stored there for the next 32 years.

The Danish potential appears to be too low, however, for use as a possible storage site for *emissions from German point sources*. In addition, the formations are a long way from German industrial locations, at over 800 km from the Ruhr. The oil and gas fields are located in the far west of the North Sea and in the (potentially unsuitable) Thisted structure in the north of Denmark. The aquifer closest to the border of Germany has already been reserved for the storage of natural gas (Toender).

7.6.3 The British and Norwegian North Sea

Infrastructure considerations

If CCS gains broad support in northern Europe, an integrated network to transport CO_2 could emerge. Amongst others, (van den Broek et al. 2009) consider whether emissions from the Netherlands, Belgium and Germany could be transported over 750 km from the Dutch coast to the Norwegian Utsira formation. The precondition for such transportation would be a European pipeline system, which would have to be financed by participating countries ((van den Broek et al. 2009) reckon with € 3.5 to € 10 per tonne of CO_2, depending on the scenario development). Norway is in favour of a state authority operating and monitoring any necessary CO_2 pipelines. The approach involving joint infrastructure assumes there is sufficient storage capacity in the Utsira formation, as discussed in detail below.

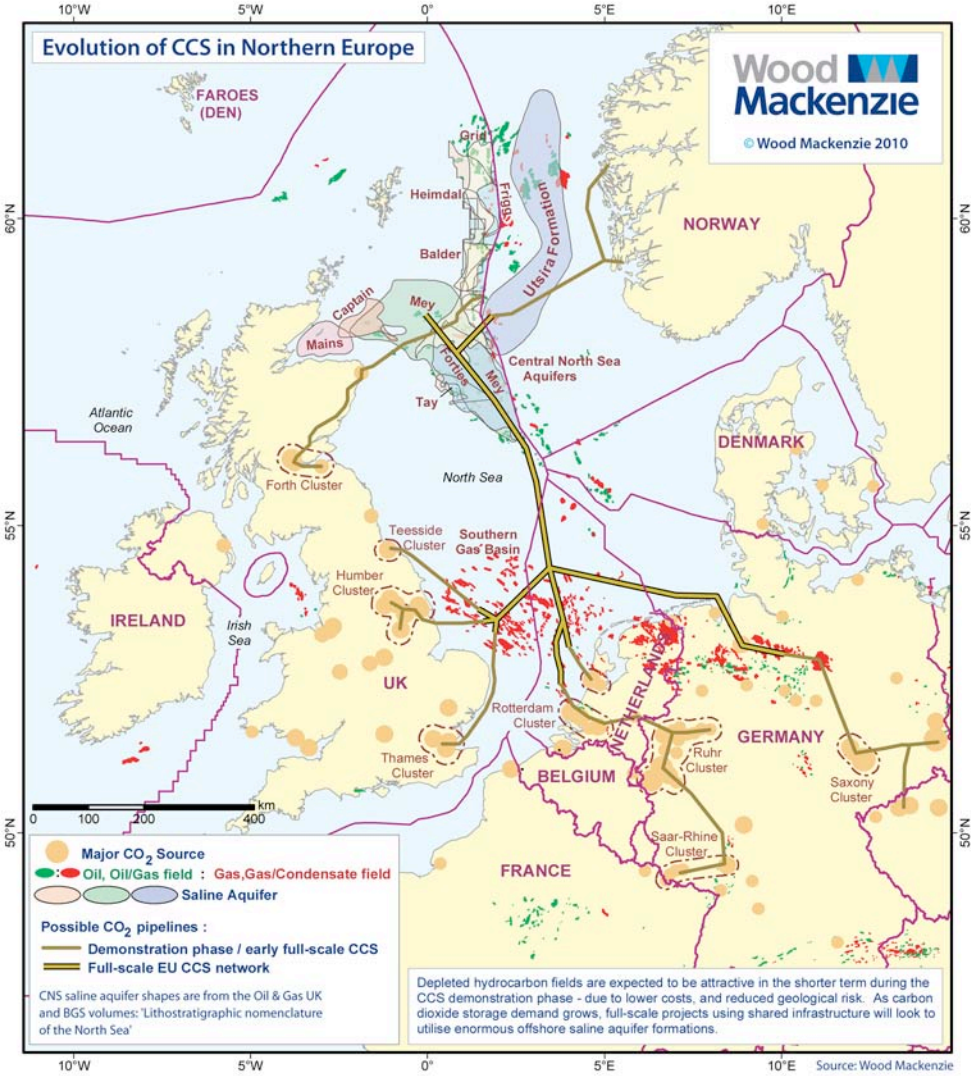


Fig. 7-11 Potential CO_2 pipeline system in north-west Europe, including large point sources, oil and gas fields, and saline aquifers.

Source: Haszeldine 2009a

Fig. 7-11 presents a proposal for a CO_2 pipeline system in Europe (Haszeldine 2009a). According to this proposal, an EU CCS continental pipeline could be established that would transport CO_2 emissions towards the North Sea via two routes. One possibility would be to transport emissions from eastern German and Polish large point sources via the natural gas fields of Lower Saxony. Another option envisages emissions from the Saar and Ruhr being transported via the Netherlands to British and Dutch fields. The two lines would meet in Dutch waters and then head together towards Norway (to Utsira and elsewhere). Great Britain would also be connected to this system. According to (Haszeldine 2009a), Utsira could be established as a large pan-European storage site for future decades and could take in emissions from north-west Europe and maybe elsewhere.

Plans for the infrastructure assume there is sufficient storage space in the North Sea. Several authors assume in their studies that there is sufficient potential in Norway and the United Kingdom. Estimates of the storage space for CO_2 vary considerably, depending on the re-

spective assumptions, and those for these two North Sea states are discussed in detail below. It could be easier, safer and possibly even cheaper to store CO_2 offshore rather than onshore (Schrag 2009) because these areas are uninhabited, and it would be very easy to classify and investigate the structures.

United Kingdom of Great Britain and Northern Ireland

Deep saline aquifers

The storage capacity in deep saline aquifers is estimated using two approaches: a "top-down" and a "bottom-up" approach. Only the geological formations beneath the British North Sea are considered because there are virtually no storage conditions on land.

1. Top-down approach:

The most feasible geological option for storing CO_2 in the North Sea is in saline aquifers. The ACCSEPT Final Report (Anderson et al. 2007) explains the differences in the estimates undertaken in the JOULE II Report, amongst others (van der Straaten et al. 1996). If the absolute pore volume of all potential reservoirs is available for storage, a theoretical capacity in aquifers in the British North Sea of 240 billion tonnes of CO_2 is yielded. In the report, this unsatisfactory approach is compared with a trap-based method in which only structural traps in the aquifers can be used to store CO_2. Then only part of the pore space is available, leading to an effective capacity of 8.6 billion tonnes (3.6 per cent of the theoretical capacity).

GESTCO calculates the storage capacity in the largest aquifers of the UK to be 89.4 billion tonnes of CO_2 (with an efficiency factor E = 40 per cent). Restricting this amount to trap structures would reduce this CO_2 storage potential in the Rotliegend of the southern North Sea to 14.3 billion tonnes of CO_2. This figure is also confirmed in a study by (Bentham 2006).

The GeoCapacity report assumes comparative values – 14.9 billion tonnes of CO_2 in all formations (including the Irish Sea). In a rough estimate, the Irish Sea is initially excluded, leaving only the southern North Sea with a value of 14.2 billion tonnes of CO_2. This capacity is reduced by a blanket rate of 50 per cent to exclude any uncertainties (for instance, storage sites with unsuitable cap rock). A CO_2 storage potential of 7.1 billion tonnes is then yielded for aquifers in the United Kingdom (see Tab. 7-9).

Another estimate of the storage capacity of the British Rotliegend is generated in a model by (Chadwick et al. 2009). The pore volume in closed structures is given as 110 billion m^3, which creates a capacity of approximately 70 billion tonnes of CO_2.

2. Bottom-up approach:

The sinks for CO_2 in suitable saline aquifers of the North Sea are estimated by the Scottish Centre for Carbon Storage as being between 4.6 and 46 billion tonnes of CO_2 (with efficiency factors of 0.2 and 2 per cent, respectively) (SCCS 2009b). This estimate of the storage capacity is based on ten suitable formations considered to be representative for the Scottish part of the North Sea.

According to BERR (Pershad and Slater 2007), 292 potential sinks in the whole of the North Sea offer space for 35.5 billion tonnes of CO_2. The saline aquifers in UK waters make up the largest part, with 14.5 billion tonnes of CO_2. Only 67 structures remain if those larger than 100 million tonnes alone are considered.

The theoretical capacity of 89.4 billion tonnes estimated by GESTCO (see above) would then decrease to 86.4 billion tonnes of CO_2, yielding an effective storage capacity of 13.8 billion (rather than 14.3 billion) tonnes of CO_2.

The British Geological Survey (BGS) regards the existing capacity estimate for saline aquifers in the UK as not having been adequately addressed yet (Holloway 2009). "Several billion tonnes of CO_2" are given as quantitative data. Although the existing studies take the pore volume and the saturation of CO_2 in closed formations into account, they neglect the potentially limiting factor of regional pressure propagation. This is particularly relevant when upscaling in the bottom-up approach, because a total capacity is drawn there from a certain fixed number of smaller structures. Above all, the pore pressure is expected to play a decisive role if the anticipated large quantities of CO_2 are injected into the structures. It is reported that injection into an aquifer would also influence the pressure regime in neighbouring storage sites, which could reduce the potential there, leading to an overestimate of total storage capacities.

(Haszeldine 2009b) mentions that the storage capacity would be reduced by the inefficient migration of the CO_2 in the reservoir. It is considered pertinent to restrict the process to trap structures because the greenhouse gas in open formations could spread for tens of kilometres in the course of a 30-year injection period, which would increase monitoring costs considerably.

Because of this uncertainty, (Holloway 2009) is opposed to using theoretical storage capacities that are unable to withstand scrutiny. Instead, only adequately tested reservoirs with suitable geological characteristics should be included in the total capacity. Even conservative estimates show, however, that sufficient CO_2 storage capacity exists to operate CCS (Anderson et al. 2007).

Tab. 7-9 compares the most important findings of the top-down and bottom-up approaches.

Natural gas and oil fields

The calculations for CO_2 storage capacities in hydrocarbon fields do not deviate as significantly as those for saline aquifers. This is because they are based on more reliable data. The storage possibilities for CO_2 in oil or gas fields onshore are excluded because they are too small (Pershad and Slater 2007, Holloway 2009).

In the JOULE II Report, the offshore potential in gas fields was assumed to be 4.9 billion tonnes of CO_2. The Triassic Sherwood Sandstone 1, in particular, offers enormous potential. (Holloway 2009) reports 1.2 to 3.5 billion tonnes of CO_2 as the CO_2 storage capacity in the natural gas fields on the British continental shelf. The estimates by (Bentham 2006) and (Christensen and Holloway 2004) – 2.8 and 3.1 billion tonnes of CO_2 – are in a similar region.

According to JOULE II, oil fields contribute 2.6 billion tonnes of CO_2 (van der Straaten et al. 1996). (Holloway 2009), on the other hand, goes as far as to state that up to 6.1 billion tonnes of CO_2 could be stored in them. If CO_2 EOR projects were realised prior to storage, however, almost 60 of these oil fields would no longer be available (Pershad and Slater 2007). Nevertheless, after the completion of tertiary recovery, these could also be used to store CO_2.

Tab. 7-9 Comparison of CO_2 storage capacities in the United Kingdom of Great Britain and Northern Ireland (UK)

Formation		**JOULE II**	**GESTCO**	**Bentham**	**BERR**	**GeoCapacity**	**Holloway**	**SCCS**
	Year	*1996*	*2004*	*2006*	*2007*	*2009*	*2009*	*2009*
Aquifers[b]		8.6–240	14.7[a]	14.3	14.5	7.1	?	4.6–46
	Efficiency factor (%)	*6*	*40*	-	-	*40*	-	*0.2–2*
	Approach	*Top-down*	*Top-down*	*Bottom-up*	*Bottom-up*	*Top-down*	*Bottom-up*	*Bottom-up*
	Density of CO_2 (kg/m^3)	*700*	*634*	-	-	-	-	-
Oil fields		2.6	10.5	-	4.2	1.2–3.5	1.2–3.5	> 1
Gas fields		4.9		2.8	*6*	6.1	6.1	
	Sweep efficiency (%)	*100*	-	-	-	*65–90*	*65–90*	-
Total[c]		16.1	25.2	17.1	24.7	14.4–16.7	> 7.3	> 5.6

All quantities given in gigatonnes of CO_2, unless otherwise stated.

BERR = (Pershad und Slater 2007)

– = not specified

[a] = a restriction to structures > 100 million tonnes theoretical capacity reduces this to 13.8 gigatonnes of CO_2

[b] = (Chadwick et al. 2009): 70 gigatonnes of CO_2 in saline aquifers

[c] = (Haszeldine 2009b): altogether 150 gigatonnes of CO_2

Source: Authors' design

In total, the potential in hydrocarbon fields corresponds to 7.3 billion tonnes of CO_2 (GeoCapacity) or 7.5 billion tonnes (JOULE II). The result given in GeoCapacity is based on the assumption that CO_2 can only be stored in fields larger than 50 million tonnes. The capacity is then reduced from 9.6 billion tonnes to 7.3 billion tonnes of CO_2.

This restriction is also applied by (SCCS 2009b). Based on this, only 29 of 200 hydrocarbon fields in the Scottish North Sea are suitable for CO_2 injection. The six most promising formations provide a capacity of 300 to 1,000 million tonnes each. However, production for some fields is predicted only to end sometime between 2020 and 2030. Short-term availability must, therefore, also be taken into account. The oil fields are more likely to be used for CO_2 EOR rather than for the "simple" storage of CO_2. Brent oil field, however, offers a high capacity of 450 million tonnes of CO_2 and could, therefore, also be designated as a storage site (SCCS 2009b).

Total capacity

Overall, GESTCO yields a theoretical CO_2 storage capacity for the southern North Sea of 17.4 billion tonnes of CO_2. Encompassing the other North Sea areas, a total capacity of around 25 billion tonnes of CO_2 is generated, approximately the same amount estimated by BERR. JOULE II and (Bentham 2006) are more cautious, stating total capacities of around 16 and 17 billion tonnes of CO_2. The conservative approach of GeoCapacity results in just 14.4 billion tonnes of CO_2, whereby the largest share can be found in the southern North Sea. No differences between the top-down and bottom-up approach are discernible because a similar range is covered by both methods.[61]

As a conservative estimate, the GeoCapacity approach with a storage capacity of around 15 billion tonnes of CO_2 in the British North Sea is used.

Comparison with emissions and conclusion

The emissions from large point sources in the United Kingdom are currently around 260 million tonnes of CO_2 per annum (see Tab. 7-6). The conservative estimated capacity of 15 billion tonnes of CO_2 would suffice to store these emissions for 60 years. In the event of a 40-year service life, only 10.4 billion tonnes would be required – the remaining space could be used for emissions from other European countries. Should this occur, (Haszeldine 2009a) advocates making existing capacities available to other EU countries for a fee. He proposes a price of £ 10 sterling per tonne of CO_2 (currently around € 13/t CO_2).

Norway

The Norwegian mainland is an ancient crystalline continent that offers no possibilities at all for storing CO_2. However, it is a completely different matter when it comes to the offshore area, where several basins are located in the North Sea: the Viking Graben, the Central Graben and the Norwegian-Danish Basin.

Aquifers

[61] (Haszeldine 2009b) assumes completely different storage possibilities without, however, presenting the basis of calculation in further detail: it is reported that there is enough space available in the North Sea to store 100 years' worth of emissions of north-west Europe's emissions. 150 gigatonnes of CO_2 could be stored below British waters in saline aquifers and depleted oil and gas fields.

1. Top-down approach:

Several research projects have estimated the CO_2 storage capacity in the saline aquifers of the Norwegian North Sea (Tab. 7-10). JOULE II computes a potential of 476 billion tonnes, if storage is not restricted to traps. Alternatively, if only closed structures are permitted for storage, a capacity of 10.8 billion tonnes of CO_2 is yielded.

GESTCO (2004) makes a more moderate estimate for the total Norwegian pore space in aquifers to 280 billion tonnes of CO_2 (E = 6 per cent for open and 2 per cent for closed aquifers). This figure corresponds with a storage potential in traps of approximately 12.9 billion tonnes of CO_2, if an efficiency factor of 4 per cent and a 3 per cent proportion of traps is assumed for all structures. The same method was also applied in the JOULE II Report. The differences between the reports are accounted for by the variation in other parameters.

2. Bottom-up approach:

In the GESTCO Report, however, individual formations are also analysed. It remains unclear why structures (totalling 760 million tonnes of CO_2) classified as potentially unsuitable are also included in the calculation. In addition, there is no minimum field size stipulation, as was the case for the UK (Pershad and Slater 2007) and Denmark (GESTCO). If Norwegian structures must also be able to accept a minimum quantity of 100 million tonnes of CO_2 effective capacity, an additional 540 million tonnes of CO_2 storage capacity would have to be excluded. The aquifer potential is then reduced to 11.6 billion tonnes of CO_2. It should also be mentioned that there is only sparse geological knowledge for over half of the structures. This is the case in most estimates, however, and could only be remedied by undertaking field studies.

The GeoCapacity study (Vangkilde-Pedersen et al. 2009) refers to the GESTCO data, without providing a new calculation. The figure there, however, is given as 26 billion tonnes of CO_2.

Tab. 7-10 Comparison of CO_2 storage capacities in Norway

Formation		**JOULE II**	**GESTCO[a]**	**GeoCapacity**
	Year	*1996*	*2004*	*2009*
Aquifers		10.8–476	12.9[b]–280	26.0
	Efficiency factor (%)	*4*	*4*	-
	Approach	*Top-down*	*Top-down/Bottom-up*	*Bottom-up*
	Density of CO_2 (kg/m^3)	*623–769*	*769*	-
Oil fields		3.1	3.4	3.2
Gas fields		*7.2*	9.2	
Total		21–486	25–289	29.2

All quantities given in gigatonnes of CO_2, unless otherwise stated.

– = not specified

[a] = BERR (Pershad and Slater 2007) adopts these results

[b] = a restriction to structures > 100 million tonnes reduces the capacity to 11.6 gigatonnes

Source: Authors' design

The deviations in the estimates for the Utsira formation will now be presented as an example of a formation that could be the destination of a pan-European CO_2 pipeline infrastructure for many years.

An in-depth analysis of the Utsira formation

Utsira is a much-discussed geological formation in the Norwegian North Sea (see Fig. 7-11, top centre). It has excellent permeability and porosity values, enabling CO_2 to be stored there.

Since 1996, around 1 billion tonnes of CO_2 have been separated annually offshore during gas recovery at the Sleipner West gas field and buried underground between two natural gas fields in the Utsira formation. This has been necessary because the recovered natural gas has a CO_2 content of 4 to 9.5 per cent. For this reason, it must be cleaned prior to sale (Moniz 2008). The main reason behind this CO_2 injection is to avoid having to pay the Norwegian CO_2 tax for creating emissions. This would comprise almost 3 per cent of the total emissions of Norway if it were not injected underground. Injection takes place in a 150 to 200 m thick sandstone reservoir at a depth of 800 to 1,000 m. So far, small quantities have been stored there without any problems.

According to (Riis 2007), the entire emissions created by Europe over the next 500 years could be deposited in the Utsira formation. For this to happen, the formation would have to have the capacity to contain 600 billion tonnes of CO_2 (Christensen 2007). (ZEP 2006) reports that 2 billion tonnes of CO_2 have to be injected into Utsira annually. With this high potential, there would be sufficient potential for 200 to 300 years of emissions storage.

However, this figure reflects only the theoretical capacity that could be realised by the complete exchange of the formation water in the pore space by CO_2. Safe storage can only be achieved by injecting into trap structures, and taking into account the increased pressure in the formation, using an efficiency factor (van der Meer and Yavuz 2009).

JOULE II (1996) has estimated the effective storage capacity of the Utsira formation to be only 50 billion tonnes of CO_2, provided that the whole aquifer is made available. This calculation was carried out according to Equation 7.1 (Section 7.4.1) with a pore volume of 1,092 km^3, a CO_2 density of 769 kg/m^3 and an efficiency factor of 6 per cent. If only closed structures were used for storage, which make up 3 per cent of the volume, capacity would be reduced to 1 billion tonnes of CO_2, applying an efficiency factor of 4 per cent.

In the GESTCO project (2004), the estimated pore volume was 10 per cent lower (919 km^3), although all other assumptions were adopted. Hence the entire Utsira aquifer could hold around 42 billion tonnes of CO_2. If, on the other hand, storage was restricted to trap structures (3 per cent), as recommended in the report (E = 4 per cent), there would only be space for 0.85 billion tonnes of CO_2.

If smaller aquifers are considered (area smaller than 4,000 km^2), then lower efficiency factors of 0.2 to 2 per cent are produced, according to (SCCS 2009b), depending on whether they were computed dynamically or statically. In the case of dynamic calculations, the heterogeneity of a reservoir is taken into account (E = 0.56 per cent) or a maximum increase in pressure is defined (E = 0.2 per cent). Static analyses, on the other hand, yield higher values of up to 2 per cent. Such low efficiency factors would reduce the aforementioned estimate even

further. This suggestion is supported by (Thibeau 2009), who gives 1.4 per cent as a conservative efficiency factor for aquifers in the North Sea (based on Equation 7.4).

Tab. 7-11 CO_2 storage capacities in Utsira

	Unit	**JOULE II**	**GESTCO**	**Lindeberg**	**Nooner**
Year		*1996*	*2004*	*2009*	*2007*
Area	*km²*	32,000	25,000	25,000	-
Thickness	*km*	0.15	0.15	-	-
Net-to-gross	*%*	65	70	-	-
Porosity	*%*	35	35	-	-
Pore volume	*km³*	1,092	919	-	919
Denseness of CO_2	*kg/m³*	769	769	-	530
Proportion of traps	*%*	3	3	-	3
Efficiency factor	*%*	4	4	7	4
Total capacity in traps	Million tonnes of CO_2	1,008	848	40,000[a]	584

– = not specified

[a] = condition: recovery of the same magnitude of formation water

Source: Authors' design

In their reservoir models, (Lindeberg et al. 2009) assume an efficiency factor of 7 per cent, producing a storage capacity of 40 billion tonnes of CO_2 in the pore space. Here, however, an increase in pressure is balanced out by the recovery of water from the formation. An injection of 150 million tonnes of CO_2/a would have to be balanced out with a recovery of around 160 million tonnes of formation water (3 per cent salinity) annually to avoid endangering the safety of the storage site. This water would have to be pumped straight into the North Sea. It would have to be assessed whether injecting more than 40 billion tonnes of salt water over the course of the years could cause ecological problems, if the whole capacity were used. Since a much larger quantity of fresh water flows into the sea from rivers every year (296 to 354 km³), it is anticipated that the balance should not be disturbed. Problems could occur, however, due to localised high concentrations of salt. (Lindeberg et al. 2009 and Schrag 2009) do not think that this injection would be problematic, because large quantities of salt water (even impure salt water) are also pumped into oceans during oil recovery (see Section 7.5.3).

(Nooner et al. 2007) regard the density of CO_2 as one of the greatest uncertainties in estimating the mass of CO_2 that can be injected underground. Due to the increased temperature sensitivity in the Utsira formation, a density of 530 kg/m^3 is considered suitable (instead of the 769 kg/m^3 previously assumed). There is a significant proportion of impurities in the injected CO_2 (1.7 per cent), which means that the density could decline even further. This aspect of the process was nevertheless not taken into consideration. The lower density of CO_2 would reduce the effective capacity estimates in traps even further from 848 million tonnes (GESTCO) to 584 million tonnes of CO_2.

(Haugan 2009) believes that CCS technology is associated with great uncertainties. He points out the danger of leakage during or after the injection of CO_2, and believes that monitoring would be too lax. One example of such a lack of knowledge is the Tordis field to the north of the Sleipner field. Impure water is pumped into or below the Utsira formation during oil recovery. In May 2008, excessive water was injected under too high pressure, which led to the formation of a 30 to 40 m long and approximately 7 m deep fissure or crack. Oily water escaped from the formation into the North Sea. Investigations by Statoil and the Norwegian Petroleum Directorate (NPD) revealed that the Tordis field contains only offshoots of the Utsira formation and that this sediment cap was no longer existent, which was the cause of the problem. According to the (NPD 2009), however, this incident should not be used to undermine the suitability of the Utsira formation as a CO_2 storage site, as stated in (Bjureby et al. 2009). Nonetheless, the incident caused alarm because monitoring failed to register the escape in good time.

The estimate in JOULE II of around 1 billion tonnes of CO_2 storage capacity, taken from Tab. 7-11, is adopted as the conservative estimate for the Utsira formation.

Natural gas and oil fields

In GeoCapacity, the natural gas and oil fields are estimated as having a CO_2 potential of 3.2 billion tonnes, although the calculation is based on the same data as in GESTCO, which calculates 12.6 billion tonnes of CO_2 (with a 100 per cent exchange of the hydrocarbons) (Schuppers et al. 2003). Of this amount, slightly over 10 billion tonnes are in fields with a capacity greater than 100 million tonnes of CO_2. Norway is in a positive position economically in that many of these fields have not yet been depleted, and their availability has to be consolidated with the available quantities of captured CO_2 emissions. However, the maximum rate of production was already exceeded in 2001 (Schindler and Zittel 2008). The time aspects of oil recovery are addressed in further detail in Section 7.8 in connection with enhanced oil recovery.

Total capacity

The calculation for the example of the Utsira formation shows that the unusually high figures for the total storage potential for Norway of up to 486 billion tonnes (GESTCO) are most probably overestimated and that much less space is in fact available for the storage of CO_2. A reduction in capacities in the Utsira formation (conservative estimate of 1 billion tonnes of CO_2) and other saline aquifers lowers the total potential to between 21 and 29 billion tonnes, which is considered to be much more realistic.

The estimate of 21 billion tonnes of CO_2 can therefore be called a conservative effective capacity.

Comparison with emissions and conclusion

Norway has only very low emissions of 28 million tonnes of CO_2/a (compare Tab. 7-6). This shows that even the conservative estimate is considerably higher than the sinks required. If we take the figures from the GeoCapacity report (29 billion tonnes), which correspond to a quarter of the total CO_2 storage capacity in Europe, Norwegian emissions could be stored for over 1,000 years.

This figure illustrates that a European pipeline system could potentially use Norwegian storage sites, even if Utsira is, in all probability, unable to hold large quantities of CO_2. In contrast, there is the "acceptable" calculation of capacity by the (IEA GHG 2009a), which estimates a figure of less than 11 billion tonnes of CO_2 available for the whole of the North Sea up to 2050.

7.6.4 The rest of Europe

As mentioned in the introduction, only Germany's immediate neighbours could realistically have a part to play in the potential export of CO_2. Nonetheless, the storage capacities of other countries are outlined here briefly (Tab. 7-6).

Italy

Italy's geology is very much determined by the formation of the Alps. It holds two large sedimentary basins where CO_2 could potentially be stored in *saline aquifers*. These are the Mesozoic carbonates of Tuscany and the Miocene-Quaternary sediments in the Po Valley. A capacity of 0.45 billion tonnes of CO_2 (JOULE II) to 4.7 billion tonnes of CO_2 (GeoCapacity) appears possible.

The *oil and natural gas fields* are geographically dispersed and, according to JOULE II, make up a capacity of 1.8 billion tonnes of CO_2. This figure was endorsed by GeoCapacity.

In total, therefore, up to 6.5 billion tonnes of CO_2 could be injected (GeoCapacity). Compared with the low *annual emissions* from large point sources of 140 million tonnes of CO_2, this capacity could suffice for many years. The high seismic activity in Italy, however, should be taken into account in all process steps of the CCS chain, possibly restricting the usable potential and transport routes. For reasons of safety and distance, the transportation of German CO_2 via the Alps to suitable storage structures appears to be impracticable.

Spain

There is substantial storage potential in Spain, particularly in the Duero Basin in northern Spain. (Hurtado et al. 2008) estimated a storage capacity in *saline aquifers* there of between 1.67 and 11.96 billion tonnes of CO_2. Another important basin that could be used to store CO_2 is the Ebro Basin (Prado et al. 2008).

JOULE II adds to this list the Cuenca-Albacete Basin and the fringe of the Pyrenees. The first suitable estimate at the European level, however, was only achieved in the GeoCapacity report, which calculated a capacity for the storage of CO_2 in saline aquifers of around 14 billion tonnes. Less significantly, the *hydrocarbon fields* offer only minor capacities in the lower range.

With *calculated capacities* of 14 billion tonnes of CO_2, Spain has one of the largest CO_2 storage capacities in Europe. A comparison with the *emissions from large point sources* (160 million tonnes of CO_2/a) shows that the storage opportunities considerably outweigh the sources, meaning that domestic emissions could be injected for decades. Spain could utilise its high geological potential to import emissions from other countries for a fee. This undertaking, however, is restricted by its geographical location, because the Iberian Peninsula is on the edge of Europe and 1,500 km from Germany. For this reason, Spain is irrelevant as a potential recipient of German CO_2.

(South-)East Europe

The CO_2 storage capacities for several eastern and south-eastern European countries were estimated for the first time in the GeoCapacity report. These capacities are therefore subject to considerable uncertainty as they have only recently started to be explored. Nonetheless, it was revealed that CCS could be an option for reducing national emissions in several of the investigated countries since, in theory, sufficient storage space appears to be available. This is the case for *Bulgaria* (2.1 billion tonnes of CO_2), *Croatia* (2.9 billion tonnes of CO_2), *Romania* (9.0 billion tonnes of CO_2) and *Slovakia* (1.7 billion tonnes of CO_2), with emissions ranging from 5 to 67 million tonnes of CO_2/a.

Other countries with lower or no storage capacities

There are many countries in Europe with little or no storage capacities for CO_2. These include small countries such as *Luxembourg*, which is unable to store CO_2 due to the metamorphic bedrock in the north and the flat sediments in the south-west, and seismically highly active zones in south-eastern Europe, such as *Greece* and *Albania*.

Greece has a very low storage potential since the geological bedrock was greatly overprinted, folded and displaced by the Alpine orogenesis. Furthermore, the molasse formed during these processes does not offer suitable aquifers either. Seismic activities generally rule out many areas for safety reasons. Nonetheless, the potential has been estimated to be as much as 2.2 billion tonnes, at least half of which is made up of the offshore Prinos structure (GESTCO). GeoCapacity contradicts this result, and estimates that the total storage capacity would be only 250 million tonnes of CO_2, which would be insufficient for realistically considering the establishment of a CCS infrastructure. The same applies to Albania, for which GeoCapacity computes a capacity of 130 million tonnes of CO_2, and *Bosnia and Herzegovina*, with just below 200 million tonnes of CO_2.

The storage capacity for CO_2 in *Belgium* is extremely low, if not negligible. The London-Brabant Massif dominates the greatest part of the country and its ocean space. These metamorphic rocks have no porosity, and therefore do not meet any of the conditions for CO_2 storage. On the north-eastern edge of the Massif are also sedimentary layers that could possibly be used to store CO_2. Due to a lack of data, the storage capacity could not be estimated in the JOULE II Report. In more recent studies, the capacity in saline aquifers has been estimated at 100 million tonnes (GESTCO) and 200 million tonnes of CO_2 (GeoCapacity). The storage option of using coal seams is disputed. GESTCO mentions a potential of 432 million tonnes, whereas it is neglected in GeoCapacity.

The *Republic of Ireland* could store a total of only 160 million tonnes of CO_2 in offshore gas fields. This means that CCS is unlikely to play a major role there, contrary to its large neighbour, the UK. *Portugal* has small sedimentary basins which, however, lack suitable cap rocks. Small-scale CO_2 injections could be possible there offshore, however. As it is the Lusitanian country's policy not to recover hydrocarbons, this option of storing CO_2 can be eliminated.

Other negligible CO_2 storage capacities can be found in the Baltic States of *Estonia*, *Latvia* and *Lithuania* (Shogenova et al. 2009), as well as *Macedonia*, *Hungary* and *Slovenia*.

7.6.5 Conclusions from the analysis for Europe

In order to estimate the CO_2 storage potential in Europe, existing publications were assessed and their central assumptions compiled. According to these estimates, capacities in Europe are distributed very unevenly. Depending on the assumptions made in the studies, a total of between 60 and 800 billion tonnes of CO_2 storage potential is available. The potential in neighbouring countries and the North Sea are especially relevant to Germany.

As we were unable to carry out our own cautious estimates for this study, as in the case of Germany, instead we adopted the conservative estimates of the investigated studies. Some of these estimates were supplemented by our own analyses. These estimates yielded an effective storage capacity of 44 billion tonnes of CO_2 for Germany's "neighbouring states": the Netherlands, France, Denmark, the United Kingdom, Norway and Poland (see Tab. 7-12). The majority of this capacity is available in Norway, with 21 billion tonnes of CO_2 (48 per cent), followed by the United Kingdom, with 15 billion tonnes of CO_2 (34 per cent). The other countries explored have only small potential at their disposal.

The Utsira formation, with 1 billion tonnes of CO_2, is part of Norway's storage capacity. This conservative estimate assumes an effective capacity with an efficiency factor of 4 per cent and storage only in closed structures.

If the conservative estimate for Germany from Section 7.5 is added to this figure, the total capacity amounts to 49 billion tonnes of CO_2. Compared with the cumulated emissions of the analysed countries over 40 years (47.6 billion tonnes of CO_2), a virtual balance is achieved. The CO_2 storage potential would therefore have to be virtually exhausted in order to eliminate all CO_2 emissions.

Tab. 7-12 Overview of conservative capacity estimates of CO_2 storage in Germany's neighbouring countries compared with emissions from large point sources

	Unit	**Nether-lands**	**France**	**Den-mark**	**UK[c]**	**Nor-way[c]**	**Po-land**	**Sum**	**Ger-many [d]**	**Total**
Emissions [a]	*Mt/a*	92	131	28	258	28	188	725	465	**1,190**
Emissions in 40 years	*Gt*	3.7	5.2	1.1	10.3	1.1	7.5	28.9	18.6	**47.6**
Conservative storage capacity	*Gt*	3	1	1	15	21[b]	3	44	5	**49**
Remainder	*Gt*	-0.7	-4.2	-0.1	4.7	19.9	-4.5	15.1	-13.6	**1.4**

[a] = emissions from large point sources from power plants and industry (> 0.1 million tonnes of CO_2/a)

[b] = including Utsira, with approximately 1 gigatonne of CO_2

[c] = only offshore

[d] = the difference to the emissions given in Section 7.5.6 is explained by the fact that only sources with emissions exceeding 1 million t/a were considered there.

Source: Authors' design

This simplified comparison, however, disregards several difficulties:

- The *increased demand* for energy caused by the capture of CO_2 and the *CO_2 capture rate* have not been included in the estimate. If these are set at 30 and 90 per cent, respectively, the emissions needing to be captured and stored increase by 17 per cent.
- The capacities listed are *effective*, meaning that the necessary geographical matching of sources and sinks would reduce this potential yet further.
- It was assumed in the comparison that the whole quantity of emissions could be stored, which is a highly optimistic assumption if potential injection rates are scrutinised in more depth.
- In addition, the viability and costs of the necessary *pipeline system* should be reviewed (national studies on the costs of CO_2 transport generally only allow for transportation within one's own country).
- Moreover, such an approach would be a *centralistic solution*, since the majority of capacities are located in the North Sea, signalling a significant dependence on just one combined main pipeline route. It can be assumed that economic issues and public acceptance would be the decisive factors when considering a pan-European CO_2 pipeline system.
- (Lindeberg et al. 2009 and Schrag 2009) argue that the underground injection of CO_2 is only possible if the same volume of *salt water* is recovered. This generally rules out the storage of CO_2 onshore because the recovered water would also have to be stored or, after being desalinised, would lead to considerable occurrences of salification. The authors, however, believe that the recovery of salt water from deep aquifers beneath the North Sea and the resulting input of CO_2 is a possibility.
- As in Germany, other countries would not be able to capture the whole quantity of current emissions from large point sources for CO_2 storage (for the simple reason that there are legally binding targets for the growth of renewable energies in all EU countries). In order to be able to assess storage capacities realistically, therefore, similar power plant scenarios to those for Germany should be generated for other countries, and a "realistic" quantity of CO_2 matched with the conservative estimates of the storage sites.

This wide range of issues and difficulties described here show that, in all, the storage potential will probably be insufficient for the storage of all emissions. However, it appears the North Sea would have sufficient capacity to at least store some of the northern European emissions.

7.7 Atlases and cadastres on CO_2 storage capacity

A diverse range of projects are being carried out worldwide to evaluate and assess storage capacities (see Tab. 2-1). Some of the findings vary significantly, and there is a lack of clear data. For this reason, several countries are developing an atlas or cadastre on the specific subject of CO_2 storage. These atlases are being produced centrally and at the state level for the whole country.

In *Germany*, the BGR is currently involved in creating a comprehensive “storage cadastre”. With a planned publication date of spring 2011, it is not intended to resolve the question of how potential storage structures should be used. This shows that there is competition for the use of geological formations, which needs to be addressed more clearly.

In *Great Britain* the storage capacity is being thoroughly investigated by the Energy Technology Institute (ETI) in the CO_2 Storage Appraisal Project (UKSAP). The project was launched in October 2009 with an investment value of € 4 million. The study is expected to be completed in March 2011. In the project, potential offshore storage sites for CO_2 will be appraised and the capacities for the United Kingdom generated.

In collaboration with *Norway*, the UK plans to investigate CO_2 storage by matching sources and sinks in the “one North Sea” project. Its aim is to determine the scale of European demand for storage space and when this demand will arise. In addition, the project considers the development of a CO_2 infrastructure to coordinate the transboundary transport of the greenhouse gas. An atlas is to be produced providing recommendations for possible actions.

A publication by the U.S. DoE for the *USA* has been very successful. In addition to identifying suitable structures, the publication also gives an overview of the methods used to estimate the storage potential (Frailey 2008). A similar atlas is currently being prepared by the Council for Geoscience for *South Africa*. Its completion has been postponed to mid 2010.

7.8 The potential role of enhanced oil recovery (EOR) for CCS

In Section 7.6.3, the possibilities for storing CO_2 in the North Sea aquifers of Norway and the United Kingdom were considered to be immense. However, an international CO_2 pipeline infrastructure would have to be constructed in order to exploit this potential. Enhanced oil recovery (EOR) using CO_2 could start the ball rolling for this deployment. We will now proceed to give a detailed description of EOR, focusing on these two countries.

7.8.1 The different stages of oil production

Commercially, the most promising aspect of CO_2 storage is in the area of the tertiary recovery of oil and natural gas. In the first recovery stage, the natural reservoir drives cause the hydrocarbons to “bubble out” of the reservoir. In this process, between 10 and 15 per cent (North 1985) and 30 per cent (Bellona 2005) of the available oil is recovered. At 75 to 95 per cent, the production quota for natural gas is considerably higher.

In the second recovery stage, water is inserted to force out more oil. This process raises production quotas to between 30 and 35 per cent (JOULE II) or 45 and 55 per cent (SCCS 2009b). In some fields, 70 per cent of the oil originally in the reservoir can be recovered. In Norway, this rate averages at 46 per cent (Bellona 2005). In most of the oil fields in the North Sea, sea water is injected to enhance the second recovery period, whereby the injected water keeps the pressure in the field constant. This process involves a considerable amount of treatment because the water in the field blends with the oil, which could have a significant negative impact on the environment if released into the ocean without cleaning. For this reason, the polluted water is often pumped back into the formation.

In the third recovery period, gases or fluids with various chemical properties are injected into the formation to maximise oil or gas production. Today, CO_2 is mainly used to lower the viscosity of the oil and to force it out. This way, the amount recovered can be increased by a further 5 to 16 per cent of the oil originally available in the formation (Bellona 2005; SCCS 2009b). So far, naturally occurring CO_2, recovered especially, is used for such purposes, since the degree of purity plays a major role, and capture plants are not yet able to produce pure CO_2. EOR projects are proving particularly successful in the USA, and have led to the construction of a pipeline system for CO_2 of over 3,000 km. Most of the projects are located in the Texan Perm Basin. The longest pipeline (McElmo Dome) stretches 800 km (Moniz 2008). The additional recovery rates achieved there are 4 to 12 per cent of the oil originally available in the formation. This recovery method has not yet been tested offshore (SCCS 2009b).

There are different assumptions regarding the quantity of oil that can be additionally recovered using a tonne of CO_2: (Pershad and Slater 2007) cite 3 barrels of oil per tonne of CO_2 over a 25-year period of injection. (Moniz 2008) states 2.5 to 3.3 barrels, while (Balbinski et al. 2003) assume a range of between 1.3 and 6 barrels. Calculations based on (Jaramillo et al. 2009) and (Ferguson et al. 2009) show that around 60 per cent of the injected CO_2 remains underground. The remainder comes out with the recovered oil, and could be recycled. The total quantities of CO_2 required for EOR would therefore decrease.

(Holloway 2009) considers it probable that any storage of CO_2 in British oil fields will be linked to EOR, since the profit gained from the additionally recovered oil will exceed the costs of CCS. The basic requirement for the deployment of this technology is an adequate infrastructure to reliably deliver the required CO_2 at low cost. In addition, the oil price would have to remain at a high level (above US$ 100/barrel) to make enhanced oil recovery financially worthwhile (Haszeldine 2009a; Pershad and Slater 2007; SCCS 2009b). In this case, EOR could be used as a jump start for CCS.

The increased deployment of EOR could also give CCS general impetus if the storage of CO_2 is continued using the existing infrastructure once oil production has stopped (Bellona 2005). It should be pointed out, however, that large amounts of water are pumped into the oil reservoir in the course of the second recovery stage, considerably reducing the ultimate storage capacity of the formation if it is not pumped out again prior to the injection of CO_2 (SCCS 2009b).

7.8.2 Potential for EOR in Norway and the UK

Norway

The Norwegian NGO Bellona has stated that there is a great potential for EOR in Europe. According to this foundation, 175 million tonnes of CO_2 are required annually to tap an EOR potential of an additional 17 per cent of oil. In total, a production quota of 63 per cent of oil deposits would be achieved (Bellona 2005). The CO_2 would then be used gainfully as a resource. It must be said, however, that Norway has a greater potential than the UK, which is why the Scandinavian country is particularly interested in a comprehensive supply of CO_2. The method of calculating the stated potential, however, is highly simplified, because the

same quantity is not used over the whole injection period. Nonetheless, this rough estimate is useful for making an initial assessment of the North Sea EOR potential.

Until now, only 17 million tonnes of CO_2 are emitted annually from Norwegian point sources. Further emissions amounting to 9 million tonnes per annum could be made available from gas-fired power plants on the Norwegian coast. The electricity generated by these plants could be exported to its neighbouring European countries. 5 GW are currently being planned. It is not yet clear whether this additional power generated from fossil fuels would have a market, given the massive future expansion of renewable energies in the EU. On the other hand, Norwegian natural gas has a high CO_2 content. This gas would be ideal for combustion in a plant with CO_2 capture because this resource's disadvantage would then be transformed into a positive feature.

An obstacle for the large-scale use of EOR in Norway is therefore the lack of CO_2 sources. Transport to Norway proves to be difficult because EOR platforms are a long distance from the coast. In its analysis, (Bellona 2005) concludes that Norway needs as much CO_2 as possible to recover oil on the Norwegian continental shelf. Captured emissions from Denmark and Germany could also be included, which could be transported via pipeline to large EOR fields in southern Norway (Pershad and Slater 2007).

UK

The United Kingdom is also eager to realise and expand its planned CO_2 EOR projects. According to calculations, 15 to 20 million tonnes of CO_2 are required annually to tap the potential. The total injection for all possible EOR fields therefore amounts to around 1 billion tonnes of CO_2 (SCCS 2009b). This quantity could easily be supplied by capturing existing CO_2 emissions.

Christensen (GEUS) predicts an additional production of 5 to 6 billion barrels of oil through EOR in the whole of the North Sea (NPD 2007). (Pershad and Slater 2007) quantifies this potential at 3.8 billion barrels. (Holloway 2009) states that the potential for the United Kingdom is 2 billion barrels of oil that could be produced using CO_2 EOR. This amount could also increase to up to 3.7 billion barrels using additional economic incentives. This would correspond roughly to the deployment of 1 billion tonnes of CO_2 (SCCS 2009b).

7.8.3 "Window of opportunity" for CCS

(Pershad and Slater 2007) emphasise the strong time dependence of EOR sinks. Many EOR projects would be unviable because the conventional production would end several years before the establishment of a possible CO_2 infrastructure. These fields would then no longer be operated for cost reasons, and the platform would be shut down. If efficient EOR technology is to be installed, production must have ended and the associated infrastructure dismantled. Once the infrastructure has been dismantled, it is highly improbable that CO_2 will be stored there in future.

The authors divide the potential introduction of EOR in the North Sea into five phases. The first "EOR project phase" in the North Sea is set to begin in 2013, and the last to end in 2037. The fields available during the third phase (2023–2028) offer the largest capacities. (SCCS 2009b) considers it necessary to commence with EOR before 2017. This so-called "window of opportunity" will close, the more extraction advances and the end of production ap-

proaches (Balbinski et al. 2003). It makes good economic sense to commence with EOR roughly three years before production ends in a field. For large fields in the north of the United Kingdom, in other words, injections would have to start as early as in 2011, for which large quantities of CO_2 are required as quickly as possible (Holloway 2009). Since the peak of oil extraction has already passed in Norway, no time should be lost there either if the maximum quantity of oil is to be produced. It should also be mentioned that no minimum size requirement for fields in EOR projects has yet been agreed.

The offshore storage of CO_2, however, is only considered possible in fields larger than 100 million tonnes.

According to (Haszeldine 2009b), EOR works well onshore, as the USA has shown. Tax incentives are given in various states there to promote EOR with CO_2. Offshore, however, the functionality of the technology has not yet been proved. Since 2000, investigations into many fields in the North Sea have been carried out to determine their suitability for CO_2 EOR. All of them, however, failed for economic reasons (Bushby et al. 2008). This was due to the insecure supply of CO_2, the extortionate costs of converting North Sea platforms and the high investment risk, because the costs invested can only be translated into profit in the long term. So far, it has been cheaper to deploy conventional methods to produce more oil there (such as additional boreholes). (Meadowcroft 2010) also stresses that analyses of EOR activities in Norway have shown they are not financially viable, which is why CO_2 EOR projects are currently being given less attention.

7.8.4 Analogy of EOR for gas production

Enhanced gas recovery, EOR's counterpart, to extract more natural gas from storage sites is undertaken only rarely (Sim et al. 2008). To date, there is no commercial application, although the concept has already been under discussion for 15 years. Besides the previous lack of availability of pure CO_2, the greatest concern is that the injected greenhouse gas will blend with the natural gas, thereby contaminating it. In CCS pilot plants, however, some projects are also implemented using EGR (for instance, in In Salah, Algeria, see Tab. 2-1).

7.8.5 Advantages and disadvantages of EOR

The advantages and disadvantages of EOR will be compared briefly below:

Advantages of EOR

- The use of CO_2 for EOR would lead to the establishment of a suitable infrastructure; the technology is tested and further developed when the capture, transport and injection of CO_2 is demonstrated. This could accelerate the introduction of CCS.
- The technical advancement would lead to a reduction in the costs of CCS due to CO_2 EOR and profits for the oil companies, which could give CCS projects a jump start.
- It is pointed out that the use of power plant emissions for EOR could replace the use of naturally occurring CO_2, produced especially for this purpose, creating double potential for saving costs (Jaramillo et al. 2009).

Disadvantages of EOR

- It is highly improbable that EOR activities will lead to the construction of an adequate pipeline system by 2020 because the time of deployment for commercial CCS plants is continually being postponed towards 2030, meaning that such an enormous project could not be financed. The 12 planned demonstration plants are not sufficient because they are spread across various EU countries and a multitude of (short) pipelines would have to be erected from the different sites to the North Sea.
- Even if the 12 planned demonstration plants were in operation in 2020, they would only supply around 30 million tonnes of captured CO_2 annually[62]. The total amount of CO_2 required for EOR in Norway and the UK, however, is approximately 200 million tonnes annually. There would be an additional annual need of 170 million tonnes of CO_2 from 2020. Twenty large power plants would be required for this. The quantity of CO_2 captured from these plants would be needed for EOR production in the North Sea alone[63].
- The whole life cycle assessment linked to the storage of CO_2 through EOR (Jaramillo et al. 2009) concludes that between 3.7 and 4.7 tonnes of CO_2 are emitted for every tonne of injected CO_2. This amount is made up of the emissions that occur in the production, transportation, processing and combustion of oil. Unlike with the storage of pure CO_2 (if it is assumed no leakage occurs), EOR is not an option for reducing CO_2 emissions, and would therefore be at odds with climate protection (Luhmann 2009).

7.8.6 Conclusions from the analysis of EOR

There appears to be potential for enhanced oil recovery using CO_2 in the North Sea. The obstacles that need to be overcome for a large-scale deployment of CO_2 EOR offshore are the long-term, safe supply of CO_2 and a stable oil price above US$ 100/barrel. The largest capacities will probably be required in the 2020s, by which time it is highly unlikely that a CO_2 pipeline infrastructure will be in existence.

The economic incentive of EOR could promote the introduction of CCS as a climate protection option. If the EOR infrastructure is later used for CCS, the time window in which a platform can be converted must be taken into account. It must also be assessed economically whether it is worthwhile for the company to convert the platform once oil production has finally ended. If the conversion is too expensive, the infrastructure will be abandoned and the storage site may no longer remain usable.

If the life cycle assessment of EOR is considered, it is clear that it cannot contribute to climate protection. On the contrary: for every tonne of CO_2 stored, the production and subsequent use of the oil releases a four-fold amount of CO_2 into the atmosphere. The only advantage would be that by using industry emissions for EOR, the naturally occurring quantities of CO_2 previously used would remain underground and would not be tapped.

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62 This value is calculated from 12 plants the size of the planned coal-fired power plant in Hürth (capture of around 2.5 million tonnes of CO_2 per annum with a net power of 330 MW_{el}).

63 Calculated using 5 to 10 million tonnes of CO_2 per annum per power plant, on average 7.5 million tonnes of CO_2.

8 An environmental assessment of CCS compared with renewable energies

8.1 Review of the results of the RECCS study

In the RECCS study, life cycle assessments (LCAs) were carried out for the first time for the three conventional capture routes. These LCAs were then compared with selected renewable energy plants and other innovative concepts for the use of fossil fuels. Anticipated efficiency levels for 2020 were used for both the reference power plants and CCS power plants. Although the life cycle assessments were performed in line with ISO 14.040ff, they can only qualify as screening LCAs. This is because it proved impossible to obtain precise assessments for some of the processes, especially the chemical processes involved in the capture and storage of CO_2. In this study, we present the latest developments of the past three years and relevant works published after the completion of the RECCS study.

8.2 Life cycle assessments along the whole CCS chain

8.2.1 Complete overview

Our initial comparison includes life cycle assessments along the whole CCS chain. Studies that included either only greenhouse gas emissions or only the power plant without the upstream and downstream chains were not included in this exercise. The minimum criteria were:

- Life cycle assessment according to, or in line with, the relevant standards (ISO 14.040ff);
- Consideration of relevant environmental impact categories, as portrayed in (Guinée et al. 2002), for example: consumption of limited resources, greenhouse effect, acidification of soils and bodies of water, nutrient input in soils and bodies of water (eutrophication), photochemical smog, particles and dust;
- Modelling the whole chain: recovery and transport of primary energy, power plant processes (with/without CO_2 capture), transport of CO_2, storage of CO_2;
- Inclusion of second- and third-order processes, i.e. the upstream chains for individual materials (for instance, the solvent MEA) and plant infrastructure (for instance, the construction of the power plant).

Tab. 8-1 provides a comprehensive overview of the most important assumptions and findings of the studies described in the next section. Please note, however, that only the key parameters were analysed in the direct comparison. The study results may deviate from one another, due to their assuming different values. These have not been analysed in detail.

- Utrecht University: *Hard coal-fired steam power plant* in the Netherlands, including post-combustion (MEA capture), current situation, 50 km pipeline, natural gas storage facility

Tab. 8-1 Comprehensive overview of assumptions of life cycle assessments along the whole CCS chain

Authors	Unit	Wuppertal Institute 2007					Uni Utrecht 2008	FZ Jülich 2009		IFEU Institute 2009			PSI and IER 2008													
Power plants		Coal			Lignite	Natural gas	Coal	Coal		Lignite			Coal						Lignite						Natural gas	
		Steam	Steam	IGCC	Steam	CC	Steam	Steam	Steam	Steam	Steam	IGCC	Steam	Steam	Steam	Steam	IGCC	IGCC	Steam	Steam	Steam	Steam	IGCC	IGCC	CC	CC
CCS																										
Type of capture		Post (MEA)	Oxyfuel	Pre	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Oxyfuel	Pre	Post (MEA)		Oxyfuel		Pre		Post (MEA)		Oxyfuel		Pre		Post (MEA)	
Year of installation		2020					2008	2020	2020	2020			2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Type		Newly built					Newly built	Retrofit	Newly b.	Newly built			Newly built													
Reference year		2020					a) 2000, b) 2008	2010	2020	2020			2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Efficiency without CCS	%	49		50	46	60	46	46	49	46	46	48	49	54	49	54	54	54.5	49	54	49	54	52	52.5	62	65
Efficiency with CCS	%	40	38	42	34	51	35	35.5	41.5	27,8	33,4	38,7	42	49	41	47	48	48.5	42	49	41	47	46	46.5	56	61
Penalty	%-points	9.0	11.0	8.0	12.0	9.0	11.0	10.5	7.5	18.2	12.6	9.3	7.0	5.0	8.0	7.0	6.0	6.0	7.0	5.0	8.0	7.0	6.0	6.0	6.0	4.0
Capture																										
Model basis																										
Capture rate	%	88	99.5	88	88	88	90	90		90	92	90	90	90	99.5	100.0	90	90	90	90	99.5	100.0	90	90	90	90
Infrastructure considered		-	-	-	-	-	X	-		X			(X)													
Capture modelled		(X)	-	-	(X)	-	X	X		X	(X)	(X)	(X)													
Dismantling considered		-	-	-	-	-	-	n.a.		n.a.			X													
LCA data																										
Upstream energy demand		Hardcoal mix D			Lignite mix D	NG mix D	Hardcoal mix NL	Hardcoal mix D		Lausitz lignite			Hardcoal mix EU								Lignite mix D				NG mix EU	
Upstream materials		(X)			(X)	(X)	X [b)]	X		X	(X)	(X)	X													
Construction power plant		Hardcoal D			Lignite D	NG GuD D	Hardcoal NL						Ultrasupercritical				IGCC		BoA+				IGCC			
Compression								included																		
Model basis																										
Compression to	MPa	11					11	n.a.		18,7			n.a.													
LCA data																										
Compression		Only electricity consumption					Gas turbine	n.a.					Electricity consumption													
Leackage rate	t CO2/MW,a	-	-	-	-	-	23	0		0			n.a.													
Transport								nur in Sensitiv.analyse																		
Model basis																										
Capacity of pipeline	Mt CO2/a	5					30	n.a.					7.9													
Pipeline diameter	cm	95					95	n.a.					n.a.													
Distance	km	300					50	300/400		325			200/400													
LCA data																										
Construction pipeline		Natural gas pipeline					Natural gas pipeline	Natural gas pipeline		X			Natural gas pipeline													
Leackage rate		-					2.32 t CO_2/km,a	0		0			0.26 g CO2/(ton,km)													
Energy demand		X					0	0		X			X													
Storage		Overall 50% surcharge on transport						only in sensitiv.analysis																		
Model basis								50% surcharge on transport																		
Formation							Natural gas field						a) aquifer at a depth of 800 m; b) depleted natural gas field at a depth of 2,500 m													
Infrastructure considered							As NG storage			- [a)]			-													
							6 wells						2 wells													
							3 km length																			
Injection capacity	Mt CO2/a						7.3						7.9													
Pressure at end of pipe	MPa						10.7			15			n.a.													
Compression to	MPa						15			-			a) 10.8 b) 20													
LCA data																										
Energy demand							Electricity mix NL			0			Electricity mix													
Leackage rate	%	0					0			0			0													
Life Cycle Assessment																										
Method		UBA					CML	CML 2001		n.a.			-													
Normalisation		-					Netherlands	Germany		-			-													
Impact categories c)		6					10	6		5			-													
Contribution analysis		X					X	-		-			X													
Sensitivity analyses		X	-	-	-	-	X	X		X			-													

a) Assumption: Use of existing EOR infrastructure as available in the Weyburn-EOR project in USA/Canada
b) Characterisation factors for MEA added in CML
c) Details see next table
X = applied, available; (X) = partly applied; - = not considered; n.a. = not available
NG = Natural gas
Sources: Wuppertal Institute 2007 (WI et al. 2007); Uni Utrecht (Koornneef et al. 2008b); FZ Jülich (Schreiber et al. 2009); IFEU Institute (Pehnt and Henkel 2009); PSI and IER (Bauer et al. 2008)

Source: Authors' design

- Forschungszentrum Jülich: *Hard coal-fired steam power plants*, including post-combustion reference case, situation in 2020
  - steam power plant from 2010, retrofitted with MEA capture in 2020,
  - steam power plant in 2020 with MEA capture (new construction)
- IFEU Institute Heidelberg: *Lignite-fired power plants* in eastern Germany (Lusatia), situation in 2020, 325 km pipeline, natural gas storage facility
  - steam power plant with post-combustion technology based on MEA capture,
  - steam power plant (oxyfuel),
  - IGCC with pre-combustion technology based on Selexo
- Paul Scherrer Institute (PSI), Villigen, Switzerland / Institute of Energy Economics and the Rational Use of Energy (IER), University of Stuttgart: *Hard coal-, lignite- and natural gas-fired power plants*, 200 and 400 km pipeline, 2,500 m natural gas storage facility and 800 m aquifer
  - hard coal with post-combustion, pre-combustion and oxyfuel technology,
  - lignite with post-combustion, pre-combustion and oxyfuel technology
  - natural gas with post-combustion technology.

8.2.2 Overview of the individual studies

Hard coal (Utrecht University)

A detailed and very well documented life cycle assessment analysis for a *hard coal-fired steam power plant,* including post-combustion and subsequent transportation and storage of the CO_2, was published in 2008 by scientists at Utrecht University (Koornneef et al. 2008b). Three cases were explored:

1. Reference case: average hard coal-fired steam power plant operating in the Netherlands in 2000 (subcritical, 460 MW_{el}),
2. State-of-the-art hard coal-fired steam power plant (ultra-supercritical, 660 MW_{el}),
3. as in Case 2, but fitted with MEA-based, downstream CO_2 separation (post-combustion, capture rate 90 per cent, net 450 MW_{el}, capture of 3.6 million tonnes of CO_2/a).

In contrast to the RECCS analysis, rather than modelling a future situation in 2020 (with/without CCS), an analysis was made of what a state-of-the-art coal-fired power plant (with/without CCS) could achieve compared to actual reality. The model focused on the capture of CO_2. To this end, existing life cycle assessment modules for hard coal-fired power plants were first updated using as their model the state-of-the-art system in flue gas cleaning in the Netherlands to create a starting point for Case 3. As an upstream chain, the average hard coal mix for the Netherlands from 2004 was used.

With regard to *CO_2 capture*, the equipment required for the infrastructure was modelled according to manufacturers' data. This model excluded energy expenditure for construction and dismantling, and also energy consumption and material costs for maintenance, excluding later disposal. In addition, the demand for heat and electricity was determined. The capture

process was modelled in detail using data from published works (consumption of MEA and degradation to salts, reaction with other emissions in addition to CO_2, consumption of other materials).

The *compression process* was modelled using LCA data for a gas turbine; the energy expenditure for compression with an initial pipeline pressure of 11 MPa was calculated in detail. Based on the IPCC method (IPCC 2006), a leakage rate in the compression of 23 t CO_2/(MW,a) was established. With an assumed capture quantity of 3.6 million tonnes of CO_2/a (or 0.011 million tonnes of CO_2/(MW,a)), this constitutes a 0.4 per cent loss of CO_2.

A distance of 50 km was assumed for the *transport*. This distance was considered representative of a pipeline from a coastal location to one of several possible onshore storage sites in northern Holland. The infrastructure was modelled in line with the natural gas pipeline. A leakage of 2.32 t CO_2/(km,a) was assumed. With a total transport of 30 million tonnes per annum, for which the pipeline was designed, this produces a leakage rate of 0.0000077 per cent per kilometre transported.

When assessing *CO_2 storage* in a depleted natural gas storage site, the infrastructure was modelled based on experience gained from storing natural gas (excluding energy expenditure for construction and later dismantling, excluding energy expenditure and material costs for maintenance, excluding subsequent disposal). In addition, the installation and operating expenses for six 3 km boreholes were included. It was taken into account that the pressure at the end of the pipeline is insufficient for injecting and that a pressure boost from 10.7 MPa to 15 MPa is required, using electricity from the grid. Instead of modelling leakage, a leakage rate of zero or an “insignificant amount” was assumed.

The *life cycle impact assessment* was carried out using the CML process, one of the most commonly used methods of analysis. Ten different environmental impact categories were considered and standardised for the Netherlands. In addition, sensitivity analyses were performed for six critical parameters.

The *key conclusions* drawn from the study are:

State-of-the-art hard coal-fired power plants (Case 2) improve all impact categories compared with the average power plant fleet in the Netherlands (Case 1) by 23 to 83 per cent. It is not possible to make such unequivocal statements for *CCS-based power plants* because there are a number of trade-offs: if applied today, CCS could reduce the *greenhouse gas emissions* of a hard coal-fired power plant to 243 g (CO_2-eq)/kWh_{el}. Compared to Cases 1 and 2, this constitutes a 78 and 71 per cent reduction, respectively. This is much less than expected for a CO_2 capture rate of 90 per cent because of the additional emissions from the hard coal upstream chain, and other processes. These figures correspond roughly with the results in the RECCS study, which determined a reduction of 67 per cent for power plants in 2020 (for which a 49 per cent initial degree of utilisation and a CO_2 capture rate of 88 per cent were assumed).

In this context, the authors introduce the term *avoidance efficiency.* The avoidance efficiency, 68 per cent in this example, implies that only 68 tonnes of CO_2 would be avoided if 100 tonnes of CO_2 were stored. They correctly point out that this should be taken into account in the calculation of CO_2 allowances.

The impact of infrastructure expenses (capture, transport and storage) on the total greenhouse gas emissions is very low at 0.3 per cent.

If we compare Case 3 (CCS) and Case 2 (state of the art) with the other impact categories, the authors conclude that only “marine aquatic ecotoxicity” is reduced (by 27 per cent). This was caused by the reduced emissions of hydrogen fluoride. All other impact categories deteriorate by 27 to 181 per cent, although the direct emissions of dust, SO_2, hydrogen chloride and hydrogen fluoride also decline, due to CO_2 scrubbing.

Despite the detailed modelling of the various stages in the process, many uncertainties remain. For this reason, the authors call their study “advanced screening LCA”. Thus the MEA upstream chain taken from the ecoinvent database is considered to be highly uncertain. It was also not possible to explicitly model the entire capture process (the quantity of MEA used, for instance). Sensitivity analyses show that the variation for some of the parameters (for example, the CO_2 capture rate or the capture efficiency of other chemicals) has a considerable impact on the computed results. For this reason, the authors recommend the introduction of a comprehensive measurement programme for the first CCS power plants to gain information about the actual emissions caused or reduced due to capture, and about their interaction with other scrubbing technologies. In this sense, the aim of their study has also been to expose which areas have an urgent need for action.

Hard coal (Forschungszentrum Jülich)

Hard coal-fired steam power plants, including post-combustion, were also the focus of an analysis published by scientists from Forschungszentrum Jülich in 2009 (Schreiber et al. 2009). Five cases were explored:

1. Reference case: A hard coal-fired steam power plant (500 MW_{el}) installed in the 1990s, but still in operation in 2005,
2. A state-of-the-art hard coal-fired steam power plant, installed in 2010 (552 MW_{el}),
3. A hard coal-fired steam power plant projected to standards for 2020 (697 MW_{el}),
4. As in Case 2, but retrofitted in 2020 with MEA scrubbing (90 per cent capture rate, net 426.5 MW_{el}),
5. As in Case 3, but fitted with MEA scrubbing (90 per cent capture rate, net 592 MW_{el}).

As in the previous study, a comparison was drawn between a brand new, state-of-the-art coal-fired power plant (both with and without CCS) and a more realistic, older plant. To this end, the power plant was divided into its various modules, and the individual units – such as the generator, flue gas scrubbing and dust scrubbing – were projected and supplemented by CO_2 scrubbing, including CO_2 compression for Cases 4 and 5. The average hard coal mix for Germany was used as the upstream chain. Neither transport nor storage was considered in either of the basic variants for CCS. The presentation of results focused on the separation of emissions and consumption in the actual power plant process and all upstream and downstream processes.

The additional need for heat and electricity was determined with regard to *CO_2 capture.*[64] In Case 5 (CCS new construction), the SO_x concentration in the flue gas was reduced from 150 to 29 mg/m^3 for the capture process. The consumption of NH_3 and limestone, as well as MEA and caustic soda (for CO_2 capture), was varied. The infrastructure was not modelled. The energy demand for compression was included, but not explained in further detail. Leakages were not taken into account.

The *life cycle impact assessment* was also carried out using the CML method. Six different environmental impact categories were considered and standardised for Germany. The impact of other hard coal upstream chains, the addition of transport (300 km) and storage, a longer transportation distance (400 km) and a higher CO_2 absorption rate of the MEA were investigated in sensitivity analyses.

The *key conclusions* drawn from the study are:

State-of-the-art or future state-of-the-art hard coal-fired power plants (Cases 2 and 3, without CCS) improve all impact categories compared to power plant generation from the 1990s.

Retrofitting with CO_2 capture (Case 4) and the construction of a new CCS power plant (Case 5) generated a 27$^{(*)}$ and 20$^{(*)}$ per cent higher *cumulated energy consumption* than for reference power plants 2 and 3.[65] The *greenhouse gas emissions* were reduced from around 800$^{(*)}$ and 770$^{(*)}$ g (CO_2-eq)/kWh$_{el}$ to 210$^{(*)}$ and 190$^{(*)}$ g (CO_2-eq)/kWh$_{el}$, i.e. by 74$^{(*)}$ and 75 per cent$^{(*)}$. The relatively low additional consumption and the relatively high greenhouse gas reduction in Case 5 are due to the low efficiency loss of just 7 per cent. Retrofitting with losses of just 10.5 per cent was probably also calculated too generously because these values have already been exceeded by other authors for newly constructed power plants.

If Case 4 (CO_2 retrofitting) is compared with Case 2 (state of the art) with regard to the other impact categories, the authors conclude that all categories would worsen by 6$^{(*)}$ to 210$^{(*)}$ per cent. If, on the other hand, Case 5 (CCS new construction in 2020) is compared with Case 3 (new construction in 2020), the summer smog category improves by 13$^{(*)}$ per cent, whereas the other categories deteriorate by 5$^{(*)}$ to 90$^{(*)}$ per cent.

Sensitivity analyses show that the consequences of transport and storage[66] have only a minor effect on all impact categories. Varying the solvent's absorbency does not cause any noticeable change. Only the use of Australian or South African coal instead of the German hard coal mix leads to a 40$^{(*)}$ to 120$^{(*)}$ per cent reduction in acidification, summer smog and eutrophication.

Lignite (IFEU Institute)

Shortly afterwards, scientists from the Institute for Energy and Environmental Research, Heidelberg, published a detailed life cycle assessment analysis for various CCS-based *lignite power plants* (Pehnt and Henkel 2009). The analysis is based on the work of (Henkel 2006)

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64 No sources were given for this, however.

65 All of the following values marked with (*) can only be estimated since they are not available as numerical values, but have to be measured from diagrams.

66 Storage is modelled in accordance with the approach in the RECCS study, in which, for cost estimates, 50 per cent of the energy consumption and the emissions balanced for transport were applied for storage.

and (Idrissova 2004). The analysis refers to 2020 and lignite mined in Lusatia. The following were analysed:

1. A steam power plant with and without post-combustion technology based on MEA capture (90 per cent CO_2 capture rate),
2. An oxyfuel-based steam power plant (92 per cent CO_2 capture rate),
3. An IGCC with and without pre-combustion technology based on Selexo (90 per cent CO_2 capture rate),

all of which were designed with a capacity of between 500 and 800 MW_{el}. As in the RECCS study, the current state-of-the-art example was first projected on to 2020 for the steam power plant and IGCC (efficiency and emissions) to model the capture of CO_2 and then expanded by a CCS variant. In addition to these reference conditions, “slower development” and “faster development” routes were considered (with/without CCS) as a sensitivity analysis. Lusatian lignite was used as the upstream chain.

The CO_2 capture was modelled in different ways:

- Steam power plant (post-combustion): MEA manufacture, consumption and degradation, CO_2 capture rate and energy consumption, capture of other emissions, infrastructure. Compared to all other studies, the very high level of energy consumption is conspicuous (18.2 per cent efficiency losses, which lead to an increased consumption of 66 per cent).
- Steam power plant (oxyfuel): oxygen requirement and energy consumption for air separation, CO_2 capture rate, SOx separation, 92 and 100 per cent retention of all other emissions in sensitivity analyses, infrastructure.
- IGCC (pre-combustion): capture rate and energy consumption, SOx emissions, infrastructure.

For *compression* and *transportation*, data was imported from the Weyburn EOR project (USA/Canada), as this was deemed to be representative for Germany, too: 325 km pipeline transportation, compression to 18.7 MPa at the power plant using electricity to ensure a pressure of 15 MPa, sufficient for the injection, is achieved at the end of the pipeline. No CO_2 losses are assumed during compression and transportation; the infrastructure is not modelled.

No expenditure was assumed for *CO_2 storage* in a depleted natural gas storage site. Instead, it was assumed that the existing infrastructure from the previous recovery of natural gas could continue to be used. Since the pipeline pressure is adequate, no energy consumption is required for storage either. No leakages were modelled.

Six different environmental impact categories were considered when carrying out the *life cycle impact assessment.* Emissions in water and the soil were not included. All results were given for the reference case and two sensitivity cases “slower development” and “faster development”.

The key conclusions drawn from the study are:

Depending on the technology, between 24 (IGCC) and 66 per cent (steam power plant) additional consumption of *primary energy* is required for the CCS-based power plants.

The *greenhouse gas emissions* can be reduced from approximately 940 g (CO_2-eq)/kWh_{el} to 190(*) (post-combustion) and 120(*) g (CO_2-eq)/kWh_{el} (oxyfuel), or around 80(*) and 87(*) per cent.[67] The IGCC power plant was 880 g (CO_2-eq)/kWh_{el} and is reduced to 140(*)g (CO_2-eq)/kWh_{el}, i.e. by 84(*) per cent. The difference to the assumed CO_2 reduction rates of 90 to 92 per cent is revealed by the expenses incurred by the additional energy consumption. In contrast to hard coal-fired power plants, most emissions occur directly at the power plant (79 per cent with post-combustion and oxyfuel, and 98 per cent with pre-combustion) and not in the upstream fuel chain.

The values for the steam power plant correspond with those of the RECCS findings (although there not such a high additional consumption was assumed); the other two routes were only considered for hard coal and not for lignite in RECCS.

Potential leakages were not modelled. Nevertheless, it is assumed that CO_2 is released ("it is clear that leakage will not be zero"), albeit at a much later stage. However, it is pointed out that some research suggests that a delayed release of CO_2 emissions could have a positive impact on climate change (the slow escape of small quantities instead of higher rates at the present time). It is also stressed that the lower the permeability of the storage site, the more CO_2 is dissolved, which is then unable to reach any leakage points. This, however, contradicts the catalogue of available criteria for the selection of suitable storage sites (see Tab. 7-2). One of these criteria is that a sufficiently high level of permeability is required to be able to store huge quantities of CO_2 from power plants within a short space of time.

At 2.3 to 2.6 per cent, the proportion of infrastructure expenses within the overall greenhouse gas emissions is low. However, it is still one order of magnitude higher than the values offered by (Koornneef et al. 2008b), even though transport and storage have not been reconciled. If compression is assigned to the power plant, transport and storage (without infrastructure), it constitutes 0.1 to 2.8 per cent of the total impact.

As with (Koornneef et al. 2008b), there is a wide variety of trade-offs in the case of *other impact categories*. Depending on the technology, very different results are produced, which are analysed in detail by the authors and can only be given here for the reference case:

- Steam power plant (post-combustion): With the steam power plant, the environmental impacts in the reference case increase more or less substantially, with the exception of acidification (summer smog +250 per cent, eutrophication +98 per cent(*), acidification -5 per cent(*), health effects +26 per cent(*)). The main causes are the additional energy consumption, the CO_2 capture process and the manufacture of the solvent.
- Steam power plant (oxyfuel): In contrast, oxygen combustion generates the lowest emissions (summer smog -56 per cent(*), eutrophication -80 per cent(*), acidification -76 per cent(*), health effects -22 per cent(*)) in the reference case (92 per cent retention of all emissions).
- IGCC (pre-combustion): The environmental impacts of an IGCC *without* CCS are 33 to 66 per cent lower in the reference case than a steam power plant *without* CCS. *With* CO_2 capture, the environmental impacts increase in the reference case, as with the

67 All of the following values marked with (*) can only be estimated since they are not available as numerical values, but have to be measured from diagrams.

steam power plant (summer smog +40 per cent(*), eutrophication +20 per cent(*), acidification +66 per cent(*), health effects +27 per cent(*)), but nevertheless remain far below the values for the steam power plant *without* CCS in all categories.

In the case of the steam power plant, the results are comparable to those computed in the RECCS study; the other two routes were only modelled with regard to energy consumption in RECCS.

The authors point to the considerable uncertainties that must be taken into account when interpreting the results, in particular because IGCC and oxyfuel combustion are technologies that are still in their infancy, or have not yet been constructed. In addition, the results of the oxyfuel power plant are heavily reliant on whether non-CO_2 emissions can be fully retained, as with CO_2, or not at all. In the former case, realistically an oxyfuel power plant would be a "near zero"-emission power plant. In the latter case, it would be assessed as being similar to, or worse than, the post-combustion process.

Hard coal, lignite, natural gas (EU NEEDS study by PSI and IER)

The most extensive study, also published in 2008, was carried out within the EU NEEDS[68] project, part of a global framework to derive new "external cost" factors for future power generation systems in Europe. The potential of various CCS technologies was modelled within the context of long-term scenarios up to 2050 (2005, 2025 and 2050). Based on the scenario development, costs were computed and their life cycle assessments (or life cycle inventories) determined (Bauer et al. 2008). Three main scenarios representing potential developments from the perspective of CCS technology were considered: "pessimistic", "optimistic-realistic" and "very optimistic". The "optimistic-realistic" option, analysed below, was taken to be the most likely, as with the other technologies explored in the NEEDS study. In addition, driving and constraining forces, as well as the general role of fossil electricity generation in future energy systems, were analysed.

The dynamics applied in NEEDS are its main distinguishing feature compared with all other published studies: by linking life cycle assessments to development scenarios, relevant "learning effects" on the technical side (and hence the material balance) could be taken into account. Double dynamics are created due to the fact that the background processes are also adjusted decade for decade by, for instance, including higher recycling rates for steel or an altered energy mix based on European energy scenarios in the manufacture. The path for the 440 ppm (climate protection) scenario was chosen for the following situation.

In this study, the three processes of post-combustion, pre-combustion and oxyfuel were considered for hard coal- and lignite-fired power plants; the post-combustion process was applied for the natural gas combined cycle (NGCC). The date of application for IGCC (pre-combustion) was assumed to be 2015. The complete life cycle (upstream chains of the energy sources; the manufacture, operation and dismantling of the power plants; storage) was calculated. Life cycle assessment modules from the ecoinvent database were used throughout. These modules describe the actual situation in Europe or the transportation there. Future periods were modelled in accordance with (ESU and IFU 2008). All results were divided into the manufacture, operation, fuel and dismantling of the plant.

[68] NEEDS = New Energy Externalities Developments for Sustainability, http://www.needs-project.org/.

The following assumptions were made for the reference power plants (without CCS):

1. Hard coal-fired steam power plant reference: Rostock power plant (ultra-supercritical, 350, 600, 800 MW_{el})
2. Hard coal-fired IGCC reference: Puertollano power plant (Spain), projected (450 MW_{el})
3. Lignite-fired steam power plant reference: Niederaussem K power plant, Bergheim (lignite-fired power plant with optimised plant technology, 950 MW_{el})
4. Lignite IGCC reference: Vrespva power plant (Czech Republic, 400 MW_{el})
5. Natural gas reference: Mainz-Wiesbaden power plant (400 MW_{el}).

The power plants were projected according to the three different technology scenarios "pessimistic", "optimistic-realistic" and "very optimistic" to 2025 and 2050. Several CCS variants were also modelled.[69] The degree of utilisation (with or without CCS), the CO_2 capture rate and the use of chemicals for CO_2 scrubbing are considered to be the key parameters for *CO_2 capture*. The infrastructure of the capture plants was not modelled because it generally has only a minor impact on the results of the life cycle assessment.

- The *degree of utilisation* was projected according to bibliographical references. Depending on the source of primary energy, the technology and scenario, efficiency losses between 6 and 10 percentage points were assumed for 2025 and between 4 and 10 percentage points for 2050. If the values for 2025 are compared with those of the RECCS study, between 25 and 40 per cent lower losses than in the power plants modelled for 2020 in RECCS were assumed.
- For the *CO_2 capture rates,* 90 per cent was assumed with post- and pre-combustion (RECCS: 88 per cent), as well as 99.5 per cent with oxyfuel (coal) and 100 per cent (natural gas) (RECCS: 99.5 per cent for coal).
- The consumption of MEA, caustic soda (NaOH) and activated carbon was modelled for the post-combustion capture process, but not projected to the future, due to a lack of data. Assumptions about the behaviour of NO_x and SO_x emissions were made. For the oxyfuel combustion, only the energy consumption of the air separation was computed.

Two different distances (200 and 400 km) were assumed for the *transport*. Compression at 200 km was calculated for the 400 km long pipeline. The resulting power requirement was taken from (Wildbolz 2007, Doka 2007). The infrastructure model was based on natural gas pipelines. A leakage rate of 0.26 g/thousand km was assumed, which corresponds with a value of 0.0052 per cent per 200 km, or 0.000026 per cent per km transported.

To model *CO_2 storage*, the power requirement to establish the necessary injection pressure, calculated in (Wildbolz 2007, Doka 2007), was included for two different storage formations (aquifer at a depth of 800 m and depleted natural gas storage site at a depth of 2,500 m). Leakages were not modelled. Instead, a leakage rate of zero was adopted, and it was as-

[69] Although hard coal- and lignite-fired steam power plants were modelled differently for the actual situation, no differentiation is made any longer between lignite and hard coal for future steam power plants. This means that lignite has to develop more rapidly than hard coal, in particular with regard to the degree of utilisation.

sumed that other storage sites would not be authorised and that tests and monitoring would be able to detect any leakages.

Unlike “complete” life cycle assessments, the last step – the life cycle impact assessment – was not carried out in NEEDS. The greenhouse gas potential was merely summarised from the impact factors of the IPCC. All life cycle inventory results can be retrieved from the NEEDS website, and can therefore be further processed as required.

The key conclusions drawn from the study are:

Depending on the fuel, the technology used and the scenarios considered, the application of CCS by 2050 can reduce greenhouse gases emissions from fossil fuel-fired power plants by 70 to 95 per cent, i.e. significantly. Between 26 and 192 g (CO_2-eq)/kWh_{el} were computed as resulting values for all scenarios. In the “optimistic-realistic” scenario, the lowest value in 2050 – 28 g (CO_2-eq)/kWh_{el} – was achieved for the oxyfuel steam power plant fired by lignite. By contrast, NGCC achieved 77, lignite IGCC 118 and the hard coal-fired steam power plant (post-combustion) 168 g (CO_2-eq)/kWh_{el}. Transport and storage comprise only a fraction of the total emissions.

The low greenhouse gas emissions must be seen in the context of an increased energy expenditure (plus 10 to 20 per cent in 2050) and a corresponding increase in all emissions caused by the recovery and transportation of energy sources. As also shown in RECCS, this particularly concerns the hard coal and natural gas upstream chain. A higher burden is then yielded in the total amount with numerous emissions than without CCS. It is not possible to draw more detailed conclusions from this because the study did not calculate any environmental impact parameters.

Compared to the RECCS study, a greater reduction in emissions and a lower energy expenditure are generally yielded. This is due, in particular, to the approximately 25 to 40 per cent lower efficiency losses assumed in 2025 and further improvements in efficiency by 2050. The energy expenditure of lignite-fired power plants modelled was too low: although the capture expenditure for lignite is much higher than for hard coal-fired power plants, due to the higher CO_2 emissions, the same efficiency losses were used for both.

8.2.3 Comparison of findings

Development of emissions

The findings of the RECCS study were mainly confirmed for post-combustion processes, even if in the latest studies (in particular, by Koornneef et al. 2008b) the capture and, in part, transport and storage were modelled in more detail. Substantial new findings were generated for pre-combustion and oxyfuel, despite the fact that the capture processes have not yet been considered in detail. All of the results of the emissions calculation are presented in Tab. 8-3.

The only value given in all of the studies is that of greenhouse gas emissions, consisting mainly of CO_2, CH_4 and N_2O emissions. They are particularly relevant in the case of hard coal- and natural gas-fired power plants because considerable methane emissions (CH_4) are created here in the upstream chains. This effect is intensified by the increased energy consumption of CCS power plants. Fig. 8-1 presents an overview of the development of green-

house gas emissions in the various studies (the sensitivity analyses contained in all studies are not shown). The capture rates and initial emissions in 2020 are generally assumed to be identical in all studies. Considerable deviations are visible, however, in the reduction of greenhouse gas emissions. The reason for this is that varying assumptions are made on the additional energy consumption caused by capture, and hence the reduction in the degrees of utilisation. In the NEEDS study (Bauer et al. 2008), in particular, significantly lower losses than in other studies are assumed.

The following rates of reduction of greenhouse gases are given for 2020/2025:

- Hard coal: steam (67 to 72 per cent), oxyfuel (78 and 85 per cent), IGCC (68 and 67 per cent)
- Lignite: steam (78 to 81 per cent), oxyfuel (87 and 95 per cent), IGCC (83 and 84 per cent)
- Natural gas: steam (67 and 75 per cent).

With regard to the other environmental impact categories, some of the values for post-combustion and pre-combustion increase considerably, while they also decline in some categories due to the simultaneous reduction of individual emissions during the CO_2 capture process. A considerable decrease in all environmental impacts can generally be assumed with oxyfuel capture.

Harmonisation

There is a need for harmonisation in life cycle assessment for CCS technology. We have witnessed the wide range of assumptions for capture, transport and storage, timing of the CCS process, the type of reference power plant, the choice of parameter and the varying environmental impact categories. Following the American example of assessing all state plans according to standard “Carbon Capture and Sequestration Systems Analysis Guidelines” (NETL 2005), life cycle assessment guidelines should be drawn up and used in all investigations. In Germany, the “Network on Life Cycle Inventory Data” would lend itself to this aim of uniformity. The objective of this network is to provide harmonised life cycle assessments, including in the energy sector, in collaboration with relevant stakeholders (BMBF 2008).

Data availability

Some authors recommend installing a comprehensive monitoring programme for the first CCS power plants. This way, we could gain information about the actual emissions caused or reduced by the capture of CO_2. Such information would considerably improve our understanding of the individual chemical processes, and how to model them.

Time frame

Most of the studies neglect to take into account that a commercial use of CCS (including transport and storage) is only expected to become available in 2025, or more likely in 2030. Only the NEEDS study includes a balance for the periods 2025 and 2050, albeit based on the commercial introduction of CCS in 2020.

Calculation of captured and avoided CO_2

Even though in scientific studies the captured quantities are differentiated from the quantities of CO_2 that are actually avoided, this is not common practice.[70] For this reason, the *avoidance efficiency coefficient*, as suggested by (Koornneef et al. 2008b), should be stated in all CO_2 avoidance calculations. This coefficient plays a particularly important role when CO_2 allowances are later offset within the meaning of the amended ETS Directive (see Section 6.1.2.7).

8.3 Comparison of electricity from CCS and from renewable energies

The development of fossil technologies, including CCS, will now be compared with renewable energies. Only greenhouse gas emissions are taken into account because no standardised data exists for the other environmental impact categories for CCS.

We use the results from the aforementioned EU NEEDS study, in which not only future fossil energy technologies, but also a number of renewable energies, were investigated in terms of their future development. Life cycle assessments for three stages of development were also generated, namely current technology, the situation in 2025 and the situation in 2050. As previously mentioned, the background processes were simultaneously adjusted to energy mixes arising from the various pan-European energy scenarios. From these scenarios, we use the 440 ppm climate protection scenario here. The minimum and maximum values from the three technology scenarios “pessimistic”, “optimistic-realistic” and “very optimistic” are selected. Offshore wind power (DONG Energy 2008), photovoltaics (Frankl et al. 2008) and solar thermal power plants (Viebahn et al. 2008) are used for the comparison with CCS power plants. Their greenhouse gas emissions (CO_2, CH_4 and N_2O) are shown in Tab. 8-2. The values describe a mix of various technologies, which can be referred to in the cited sources.

Tab. 8-2 Greenhouse gas emissions from solar thermal power plants, photovoltaics and offshore wind (current situation, 2025 and 2050)

	Solathermal		Photovoltaics		Wind offshore	
	2025	2050	2025	2050	2025	2050
Current	30.56		68.94		14.60	
Minimum	19.83	16.99	16.65	5.55	5.71	7.67
Maximum	20.90	17.55	36.64	7.39	11.81	6.66
Data is given in g CO_2-eq./kWh_{el}						
A mix from different technologies is shown						
Sources of basic values for CO_2, CH_4, N_2O:						
Solarthermal systems (Viebahn et al. 2008), photovoltaic systems						
(Frankl et al. 2008), offshore wind (DONG energy 2008)						

Source: DONG Energy 2008, Frankl et al. 2008, Viebahn et al. 2008, IPCC 2007 (conversion to CO_2 equivalents)

70 For instance, a representative of a large utility company declared at the Loccum CCS Conference in October 2009 that they have not yet included the additional CO_2 emissions in their calculations.

Tab. 8-3 Comprehensive overview of results of life cycle assessments along the whole CCS chain – evaluation of five different studies

	Unit	Wuppertal Institute 2007					Uni Utrecht 2008	FZ Jülich 2009		IFEU Institute 2009			PSI and IER 2008 [e)]													
Power plants		Coal			Lignite	Natural Gas	Coal	Coal		Lignite			Coal						Lignite						Natural gas	
		steam	steam	IGCC	steam	CC	steam	steam	steam	steam	steam	IGCC	steam	steam	steam	steam	IGCC	IGCC	steam	steam	steam	steam	IGCC	IGCC	CC	CC
CCS																										
Capture technology		Post (MEA)	Oxyfuel	Pre	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Post (MEA)	Oxyfuel	Pre	Post (MEA)		Oxyfuel		Pre		Post (MEA)		Oxyfuel		Pre		Post (MEA)	
Year		2020					2008	2020		2020			2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Type		Newly built					Newly built	Nachrüstung	Newly built	Newly built			Newly built													
Reference year		2020					2008	2010	2020	2020			2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Efficiency without CCS	%	49		50	46	60	46 [a)]	46	49	46	46	48	49.0	54.0	49.0	54.0	54.0	54.5	49.0	54.0	49.0	54.0	52.0	52.5	62.0	65.0
Efficiency with CCS	%	40	38	42	34	51	35	35.5	41.5	27.8	33.4	38.7	42.0	49.0	41.0	47.0	48.0	48.5	42.0	49.0	41.0	47.0	46.0	46.5	56.0	61.0
Penalty	%-points	9.0	11.0	8.0	12.0	9.0	11.0	10.5	7.5	18.2	12.6	9.3	7.0	5.0	8.0	7.0	6.0	6.0	7.0	5.0	8.0	7.0	6.0	6.0	6.0	4.0
Capture rate	%	88	100	88	88	88	90.0	90.0	90.0	90	92	90	90	90	99.5	100	90	90	90	90	99.5	100	90	90	90	90
CO2	g/kWhel	160	68	151	195	102	n.a.	135	113	n.A.			n.a.													
Reference value	g/kWhel	710	710	695	895	370	n.a	731	686	n.A.			n.a.													
Comparison with reference	%	-77%	-90%	-78%	-78%	-72%	n.a	-82%	-84%	n.A.			n.a.													
GHG (CO2 equiv.)	g/kWhel	262	176	245	198	132	243	210	190	190	120	140	213	168	117	90	169	160	156	118	41	28	133	122	93	77
of which direct emissions	g/kWhel	93	15	89	106	54	107	90	80	151	95	137	115	91	18	14	93	89	135	102	23	16	123	112	44	36
reference (CO2 equiv.)	g/kWhel	792	792	774	897	396	837	800	770	940	940	880	765	691	765	691	692	682	819	741	819	741	788	778	366	346
of which direct emissions	g/kWhel	687	687	671	878	336	750	730	620	922	822	863	691	627	691	627	629	623	809	733	809	733	782	774	325	310
comparison with reference	%	-67%	-78%	-68%	-78%	-67%	-71%	-74%	-75%	-80%	-87%	-84%	-72%	-76%	-85%	-87%	-76%	-77%	-81%	-84%	-95%	-96%	-83%	-84%	-75%	-78%
share of infrastructure	%						0.3			2,3-2,6	2,3-2,6	2,3-2,6	negligible													
avoidance efficiency b)	%						68																			
Increase in environmental impact categories c													Emissions available in the NEEDS database to calculate all environmental impact categories													
ADP	%	28 [d)]			44 [d)]		33	27 [d)]	20 [d)]	66 [d)]	66 [d)]	24 [d)]														
GWP	%	- 67	- 78	- 68	- 78	- 67	- 71	- 74	- 75	- 80	- 87	- 84														
ODP	%						55																			
HTP	%						181	210	157	26	- 22	27														
FWAETP	%						46																			
MAETP	%						-29																			
TEP	%						57																			
POP	%	94			524		27	6	-13	250	- 56	40														
AP	%	- 10			- 3		46	13	5	- 5	- 76	66														
EP	%	36			40		80	80	66	98	- 80	20														
PM10	%	2			24																					

a) the current situation is applied as the reference case
b) avoidance efficiency = kg CO2 avoided per kg CO2 injected
c) Environmental impact categories (the potential is given):
ADP = Abiotic depletion; GWP = Global warming; ODP = Ozone depletion; HTP = Human toxicity; FWAETP = Fresh water aquatic ecotoxicity;
MAETP = Marine aquactic ecotoxicity; TEP = Terrestrial ecotoxicity; POP = Photochemical oxidation; AP = Acidification; EP = Eutrophication.
d) Only primary energy
e) The "450 ppm" scenario is chosen, referring to the "optimistic-realistic" scenario
n.a. = data not available; GHG = greenhouse gas; IGCC = Integrated Gasification Combustion Cycle; CC = Combined Cycle; MEA= Monoethanolamine
Sources: Wuppertal Institute 2007 (WI et al. 2007); Uni Utrecht (Koornneef et al. 2008b); FZ Jülich (Schreiber et al. 2009); IFEU Instituet (Pehnt and Henkel 2009); PSI and IER (Bauer et al. 2008)

Source: Authors' design

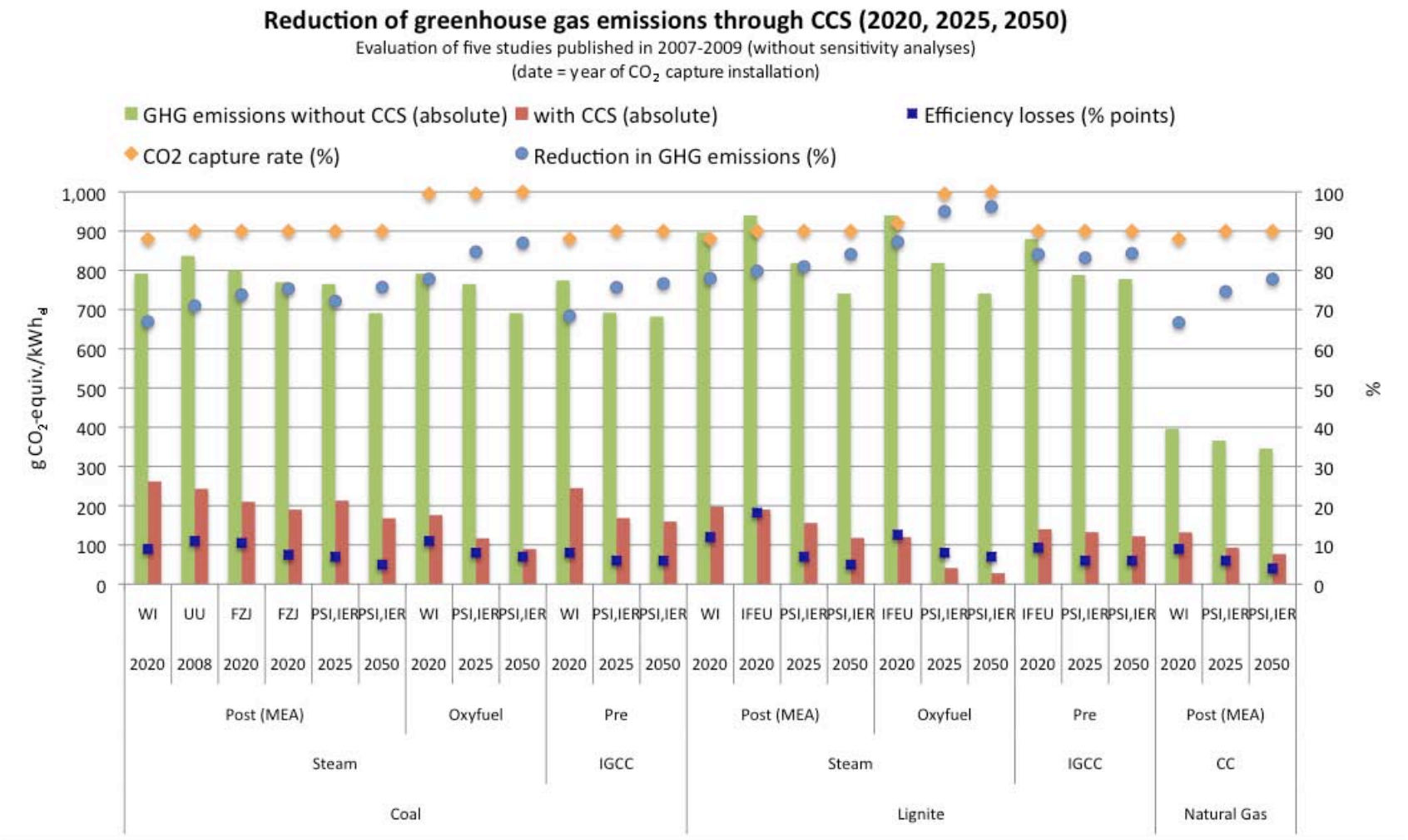

Fig. 8-1 Development of greenhouse gas emissions with CO_2 capture – evaluation of five different studies

Source: Authors' design based on an evaluation of WI et al. 2007 (WI), Koornneef et al. 2008b (UU), Schreiber et al. 2009 (FZJ), Pehnt and Henkel 2009 (IFEU), Bauer et al. 2008 (PSI, IER)

In Fig. 8-2, electricity generation from renewable energies is compared with CCS power plants in 2020/2025 and 2050. The minimum and maximum values and the mean of all options considered are given. The range given for fossil fuel-fired power plants results from combining steam power plants and IGCC from Tab. 8-3. For renewable energies, the range stems from the minimum and maximum values presented in Tab. 8-2.

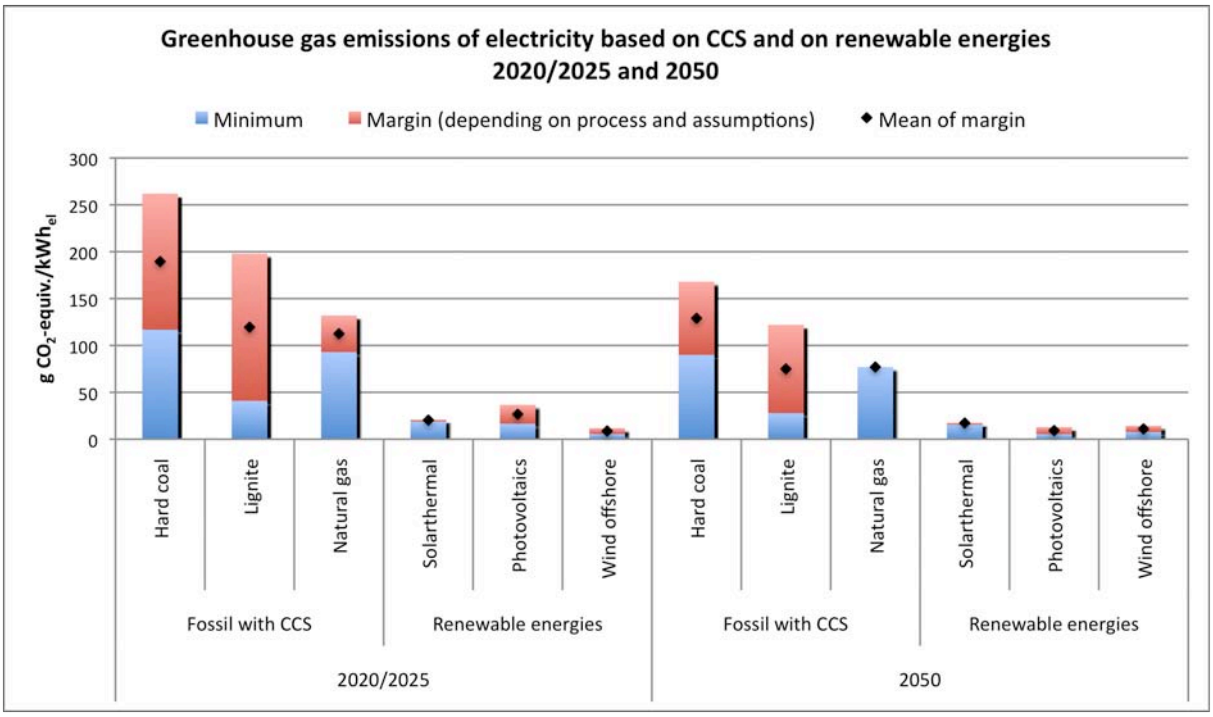

Fig. 8-2 Greenhouse gas emissions from fossil fuel-fired power plants *with* CCS in comparison with electricity from renewable energies (solar thermal power plants, photovoltaics and offshore wind (2020/2025 and 2050))

Source: Authors' design

Even compared to CCS power plants, renewable energies create only a fraction of greenhouse gas emissions (most of which originate from the construction of the plant). The chart shows that in 2025, offshore wind creates only 5 to 8 per cent, solar thermal energy 11 to 18 per cent and photovoltaics 14 to 24 per cent of the emissions of CCS power plants. By 2050, photovoltaics improve, in particular, releasing only 7 to 12 per cent of the emissions of CCS power plants; offshore wind creates 9 to 15 per cent and solar thermal energy 13 to 23 per cent.

8.4 Direct environmental impact outside LCA

Several environmental impacts cannot be evaluated using life cycle assessments. The consumption of water and cooling water, for instance, is not included in the CML method. The use of land, caused by the additional infrastructure installation and, in particular, increased coal mining, is not taken into account (Koornneef et al. 2008b).

The risks that could occur due to the transportation and temporary storage of chemicals (MEA) or the captured carbon dioxide were also neglected. These are subject to risk assessment (Koornneef et al. 2008b).

The consequences of salt water being released offshore following the injection of CO_2, dramatically increasing the local concentration of salt water, have also not yet been considered. It would have to be examined whether this would directly affect the area around the point of leakage or whether its rapid dilution with the sea water would mean that its impact was negligible (see Utsira aside in Section 7.6.3). If CO_2 is injected to enhance oil recovery, large quantities of *contaminated* salt water would also be released into the oceans (Lindeberg et al. 2009). Applied to onshore potentials, this argument is even more far-reaching: if it were necessary to extract salt water on the same scale as CO_2 is injected to keep the increase in pressure under control in aquifers, it would be extremely difficult to utilise the onshore storage capacity.

The spatial and long-term impact of the balanced emissions has not yet been considered in any of the life cycle assessments. For example, SO_2 and NO_x emissions caused by the transport of coal by sea, which have a considerable effect on the acidification and eutrophication category (Koornneef et al. 2008b), should be assessed differently to the same emissions released straight from the power plant.

Furthermore, the extent to which amines, used in the CO_2 scrubbing process, have an impact on health and the environment has not yet been adequately clarified. The gaps in our knowledge on this subject are highlighted in a study carried out by the Norwegian environmental organisation Bellona (Bellona 2009). Bellona proposes seven points that need to be clarified before CCS technology is used commercially in order to minimise or, better still, to avoid altogether, the risk of damage being caused to the environment by amines:

1. Close the gaps in our knowledge – determine the degradation routes, the degradation quantity and the retention times of the decay products of amines in the atmosphere. Determination of toxic contamination thresholds for humans, also with regard to setting tolerance limits. Determination of the degree of ecotoxicology of amines on terrestrial and aquatic ecosystems.
2. Development of amines with a low environmental impact – continuous improvement of amine scrubbing by lower energy expenditure, fewer amine-related emissions and fewer decay products than amines used previously.
3. Development of scrubbing methods with lowest possible residual emissions – the current capture rate of 85 to 90 per cent using amines in power plants should be improved even further.
4. Ensuring that the waste products from the amines are dealt with properly, because enormous quantities of hazardous waste would be created if this method were used globally.
5. Development of alternative processes – research into other capture processes, such as using membranes or chemical looping combustion, involving only minor losses of the separating agent used (see also Chapter 3).
6. Entrenchment of binding regulations – once the gaps in the knowledge outlined above have been closed, binding regulations for the operation of CCS power plants should be devised to cause minimal harm to the environment.

7. Use of CCS demonstration programmes to clarify remaining questions regarding amine scrubbing as the capture process in a CCS power plant, and its potential environmental impact.

8.5 Indirect environmental impact of coal mining and social aspects

Coal mining is generally linked to drastic, extensive changes to the landscape. In most cases, the consequences of such a restructuring of the landscape are a lowering of the water table, contamination of the water by mine drainage and the creation of enormous slag heaps that have a negative impact on groundwater supply for agriculture and the surrounding eco-systems. In addition, enormous quantities of water are consumed to wash the coal and to cool coal-fired power plants. In some areas, this has led to significant water shortages in rivers and streams.

Due to the resettlement or displacement of the population, cultivable land is lost, homes and entire village communities are destroyed, resulting in social and cultural problems. Often residents are unwilling to leave voluntarily, and forced evictions occur, often with the threat or use of violence, or even, in some extreme cases, murder.

Although the latter is not the case in Germany, resettlement causes considerable problems here, too. In the region of Lusatia in Germany, more than 100 villages with a total of over 100,000 residents have been subject to (forced) eviction for coal mining (Tagesspiegel 2009). One of the last villages to fall victim to this process was Horno, a village of around 300 residents who lost their homes despite 25 years of constant fierce resistance. In western Germany, around 7,000 people were resettled for the Garzweiler II mining project. Part of the village community disappeared, and, even though a new housing estate with newly planted gardens may seem aesthetically appealing, it will not be able to replace the sense of community and wildlife habitats, which usually take centuries to create (Welt online 2004). By deploying CCS technology in the generation of power, this problem would be aggravated further, because an 18 to 35 per cent increase in coal would be required (see Section 10.3).

In the mining process itself, sulphur, methane and dust emissions are released. Coal miners are often directly exposed to such emissions, because there are no or only inadequate safety precautions in many coal-producing countries. These emissions lead to acid rain and the formation of smog. Workers are also at risk from gas and dust explosions, as well as from flooding. In the regions affected by coal mining, increasing occurrences of respiratory diseases and skin rashes are diagnosed among workers and local residents. Once mining is abandoned, subsidence and collapses often occur, creating devastating damage to the existing infrastructure and the surrounding houses (Greenpeace 2008). When coal is combusted, residuals are created containing significant concentrations of heavy metals, radioactive substances and other substances that are harmful to nature, soils and bodies of water.

Let us now move the focus to China, which is the world's largest producer of coal. This coal output is used to meet 75 per cent of the country's electricity generation. Coal fires caused by uncontrolled mining in China lead to an average of around 6,000 fatalities per year. These fires are caused by the spontaneous combustion of coal when it comes into contact with air. In China, 10 to 20 million tonnes of coal are combusted annually, endangering workers and

local residents by the heat and emissions generated, not to mention the global damage to the climate caused by the release of CO_2 (Scinexx 2008).

Most of the world's coal fires occur in India, resulting in rising temperatures and toxic discharge into water, soil and the air. The flue gases from coal fires contain carbon monoxide, carbon dioxide, sulphur dioxide and nitrogen oxides which, together with the ever-present carbon dust, cause a variety of lung and skin diseases. The once densely populated coal-mining areas of Jharia, Ranigani and Singareni, for instance, have now degenerated into wasteland. As long as there is a supply of oxygen, these coal fires are considered to be inextinguishable (Greenpeace 2008).

8.6 Possible impact of CO_2 storage on subterranean ecosystems

It is not yet apparent whether the transportation of large quantities of carbon dioxide will have a biogeochemical impact on the microbial biota in deep rock formations. Drilling to depths of 3.5 km has revealed bacteria, viruses and fungi. These microbes can be found in quantities of up to one hundred million per gram of sediment or ground water in tiny cracks and pores in the rock (Scinexx 2004).

This field of research is very much in its infancy. Many of these types of bacteria found in deep rock formations are completely unknown. The research into their role within this ecosystem has hardly begun. It is known, however, that the metabolism of some better-known types of bacteria changes chemical compounds in deep rock. Some gain their energy by converting manganese, sulphur, nitrogen, phosphor, iron and carbon compounds (Scinexx 2004).

Several types of bacteria can transform carbon dioxide into methane. Whether these bacteria could perhaps be used to generate energy is currently the subject of a project in the GEOTECHNOLOGIES – Recobio II research programme "Investigation of the biogeochemical transformation of injected CO_2 in the deep subsurface" (see also Section 2.1.1). In this project, the significance of reduction by autotrophic bacteria for the sequestration of carbon dioxide is being explored, particularly taking into account the processes that occur in methanogenesis and acetogenesis. In addition, the impact of impurities in the carbon dioxide of these biogeochemical processes will be determined. The results will be presented once the project has been completed in spring 2011.

During a pilot storage test in a saline aquifer (Frio Brine) near Houston, Texas, research results on the mobilisation of metals and organic compounds before, during and after the injection of CO_2 were compiled by (Kharaka et al. 2009) between 2004 and 2008. It was shown that the injection of CO_2 led to considerable changes in the chemical and isotopic composition, including a dramatic shift of the pH value from 6.3 to 3.0. In addition, iron, manganese, lead and aromatic hydrocarbons reacted to the increased concentration of CO_2, and their concentrations in the formation water rose sharply.

8.7 Conclusions from the environmental assessment

In the RECCS study, life cycle assessments were carried out for the first time for the three conventional capture routes. These LCAs were then compared with selected renewable energy plants and other progressive concepts for the use of fossil fuels. The individual pro-

cesses involved in the capture of CO_2 were modelled in detail for post-combustion plants. For pre-combustion and oxyfuel, however, only the additional energy consumption is included. No new life cycle assessments were generated in this update. However, several new comprehensive life cycle assessments covering all prevalent capture routes applied to lignite-, hard coal- and natural gas-fired power plants have been presented by a number of institutions. Most of these studies were compiled in 2008. The selected studies, however, were restricted to those in which life cycle assessments of the entire CCS chain were created, following the respective ISO standards for life cycle assessments. An analysis was made of the precision with which the individual steps in the process – capture, compression, transport and storage – were modelled and also of what assumptions were made in the process.

The findings of the RECCS study were principally confirmed in the newer studies, and developed significantly. If the entire process chain, including the upstream chains of substances and energies used, is considered, the greenhouse gas emissions from CCS power plants operational in 2020 will only be reduced in total by around 68 to 87 per cent (in exceptional cases up to 95 per cent).

However, other environmental impacts should be considered in addition to greenhouse gas emissions. The higher energy consumption required in all of the processes and the materials used in the capture processes can be perceived in direct proportion to the various impact categories of the life cycle assessment. This factor was only modelled for the post-combustion process in the RECCS study. More recent studies, however, also present findings for pre-combustion (for both lignite and hard coal) and for oxyfuel. Amongst other things, these studies have explored summer smog, eutrophication, soil and water acidification, marine ecotoxicity and particle emission. Depending on the assumptions made in the studies, the various interactions in the capture processes lead to many trade-offs in the individual environmental impact categories. In some studies, all emissions increase in accordance with the additional energy consumption. Other studies, however, model trade-offs that arise from the simultaneous reduction of other emissions in the course of the CO_2 capture process.

As in the RECCS study, most of the studies conclude that for the post-combustion process increases are observed with virtually all of the environmental impacts (+26 to 250 per cent). The individual processes cannot yet be modelled in detail for pre-combustion and oxyfuel; rough estimates for IGCC show 20 to 66 per cent increases for all environmental impacts and 22 to 80 per cent decreases in all environmental impacts with oxyfuel.

The proportion related to the manufacture of the infrastructure, i.e. the plant required to capture, transport and store the gas, is analysed as being very low (0.3 to 2.6 per cent) in all of the studies. Transportation of the CO_2 is modelled more or less uniformly, even if assumptions regarding the transport distance vary. Leakages of CO_2 in the compression and transportation processes were only partially modelled. Leakages at the CO_2 storage site were neglected by all studies. It is assumed in some studies that the storage site would otherwise not have been approved. Other studies assume that CO_2 would indeed be released, albeit with a long delay, which would be significantly better for the environment than the current high rates of emission. The injection is either not modelled at all, or it is modelled only for the purpose of power requirements or for the required infrastructure.

The largely different assumptions for the CCS chain, the time of use of CCS, the type of reference power plants, the selection of various parameters and the heterogeneous choice of

environmental impact categories are particularly conspicuous. As in many other life cycle assessments, this reveals a need for action to harmonise life cycle assessments for CCS technology. Together with the German “Network on Life Cycle Inventory Data”, it is proposed that the aim of harmonising life cycle assessments should be to develop standard guidelines and to then create standard life cycle assessments for CCS reference plants based on these guidelines.

The recommendations of some authors to install a comprehensive monitoring programme for the first CCS power plants should not be restricted just to life cycle assessments. Such a programme would be important for gaining information about the actual emissions caused or reduced due to the capture of CO_2. Such information would considerably improve our understanding of the individual chemical processes, and how they should be modelled.

Even compared to CCS power plants, renewable energies create only a fraction of greenhouse gas emissions. In 2025 (2050), it is estimated that offshore wind will create only 5 to 8 (9 to 15) per cent, solar thermal energy 11 to 18 (13 to 23) per cent and photovoltaics 14 to 24 (7 to 12) per cent of the emissions of CCS power plants. All renewable energies will have improved in absolute terms by 2050, but show higher percentages, with the exception of photovoltaics, because CCS technologies will also improve.

Further aspects are also neglected in life cycle assessment. These include the fundamental, extensive changes to the landscape caused by coal mining, the consequences of a decline in the ground water table, water contamination by water from mines and the creation of enormous slag heaps that have a negative impact on groundwater supply for agriculture and the surrounding ecosystems. The resettlement or displacement of the population results in the loss of agricultural land and homes. Entire village communities are destroyed, leading to social and cultural problems.

It is not yet apparent whether the transfer of large quantities of carbon dioxide will have a biogeochemical impact on the microbial biota in deep rock formations. Drilling to depths of 3.5 km has revealed bacteria, viruses and fungi. Many of the types of bacteria found in these deep rock formations are completely unknown. Their “function” within this ecosystem has not nearly been researched to a sufficient extent.

9 Economic comparison of CCS power plants with renewable energy technologies

9.1 Update on electricity generating costs from CCS power plants and renewable energies

9.1.1 Future price trajectories for fossil fuels and CO_2 emission permits

Updated energy price trajectories are the most influential factor in recalculating electricity generating costs. The RECCS study focused on the situation prior to the oil price hike, as well as the increases in prices of natural gas and hard coal. In the RECCS study, a low price trajectory and a moderately higher "DLR 2004" price trajectory were used. In the RECCS study, the impact of prices for CO_2 emission permits was addressed in the form of a "CO_2 penalty". Taken together, these factors indicate the fuel-specific costs of using (combusting) fossil fuels, or, in simpler terms, "fuel prices (with and without penalties)".

The following recalculation is based on the cost and price calculations from the Lead Scenario 2008 (BMU 2008a). It covers a range of trajectories for future "energy prices" – a term which can be misleading, as it actually also includes the cost of combusting energy sources, determined by the prices of CO_2 permits. The lower limit of the price trajectories in the recalculation corresponds with trajectories that in 2005 were considered "high price scenarios". The energy price trajectories can generally be characterised as follows (see also Fig. 9-1):

- **Price trajectory C ("very low")**: The lowest variant – the representative development – adopts the values of the "oil price variant", used by EWI and Prognos in their Energy Report IV, adding a "high price variant" (EWI and Prognos 2006). Even this variant, however, greatly underestimated the development of the oil price. Since it is assumed in this variant that crude oil will not rise above a medium-term price level of $\$_{2005}$50-60/b by 2020/2030, it was given here, and in the Lead Scenario, as a "very low" scenario. Whereas natural gas prices remain virtually constant, a subtle increase in the price of hard coal is perceptible.
- **Price trajectory B ("moderate")**: The moderate variant takes into account a "moderate increase" in the prices of fossil fuels, and resembles the high price trajectory in the World Energy Outlook 2007 (IEA 2007). Based on the 2007 average, it was then projected forwards into the future. From today's perspective, however, it too probably underestimated the future rise in prices (BMU 2008a).
- **Price trajectory A ("considerable")**: For this reason, an upper variant with a "considerable increase" was devised, slightly above the high price trajectory in (IEA 2007). On the basis of real prices, it constitutes a doubling of the natural gas price and a more than three-fold increase in the price of hard coal.

The future price ratios of crude oil to natural gas and of crude oil to hard coal, and the longer-term development of the euro/dollar exchange rate are also taken from the Lead Scenario 2008. These rates were taken from policy scenarios (UBA 2007, Horn and Diekmann 2007) and projected ahead to 2050. It was assumed in the policy scenarios "that hard coal will not

be decoupled from the price increase of crude oil but, on the contrary, will increase by 2010 to around 40 per cent of the thermal equivalent price of oil and will remain at this level. Natural gas will also adopt the price increases of crude oil more strongly than in the past, and will peak at up to 85 per cent of the respective price of crude oil." In a departure from considering individual costs, a feasibility principle was pursued for both natural gas and hard coal.[71]

Fig. 9-1 shows the range for the three scenarios (real values in 2005 prices). The oil price trend is not shown here because it is not directly used in this study. The price trajectory for lignite, however, is included. Since lignite is mined in Germany, its price increases only marginally. It is relevant, however, as soon as price penalties for CO_2 allowances are considered.

The values shown in the following graphs can be found in the Appendix in Tab. 13-1.

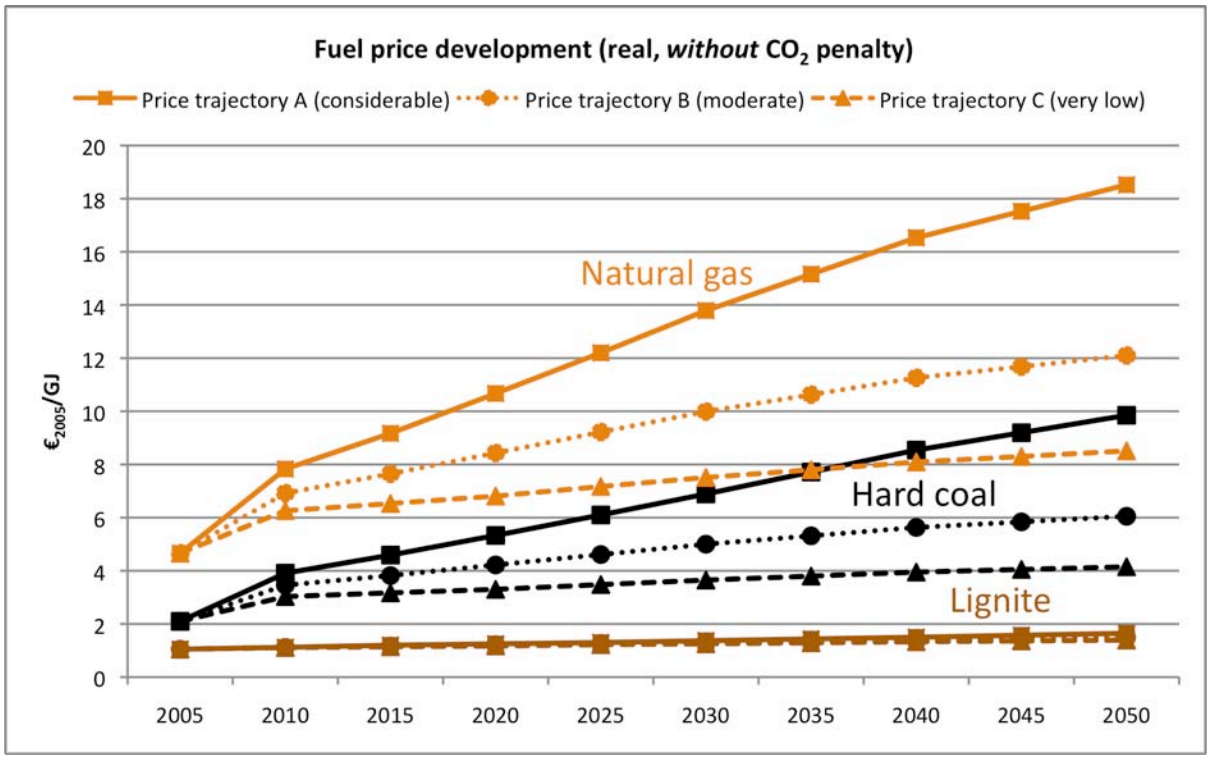

Fig. 9-1 Prices for natural gas, hard coal and lignite at power plant for price trajectories A, B and C (without CO_2 penalty)

Source: Based on BMU 2008a

In addition to the increase in actual fuel prices, the price trends for CO_2 allowances must also be taken into account. The prices chosen are taken from the Lead Scenario which, in turn, were based on policy scenarios (Horn and Diekmann 2007):

- **Price trajectory C ("very low")**: In this scenario, CO_2 penalties increase from € 15/t in 2010 to € 20/t in 2020 and to no more than € 28/t in 2050. As such, they represent the lower limit of expected future prices.
- **Price trajectory B ("moderate")**: In the moderate scenario, the prices of € 20/t (2010), € 30/t (2020) and € 45/t (2050) are mid-range.

[71] This means that hard coal prices no longer follow actual costs, but feasible costs that could be achieved compared with an oil price development.

- **Price trajectory A ("considerable")**: In price trajectory A, the expected CO_2 prices increase steadily from € 24/t (2010) to € 39/t (2020) and € 70/t in 2050. They represent the upper limit of the future development.

Fig. 9-2 shows the differing CO_2 penalties (also real values in 2005 prices).[72]

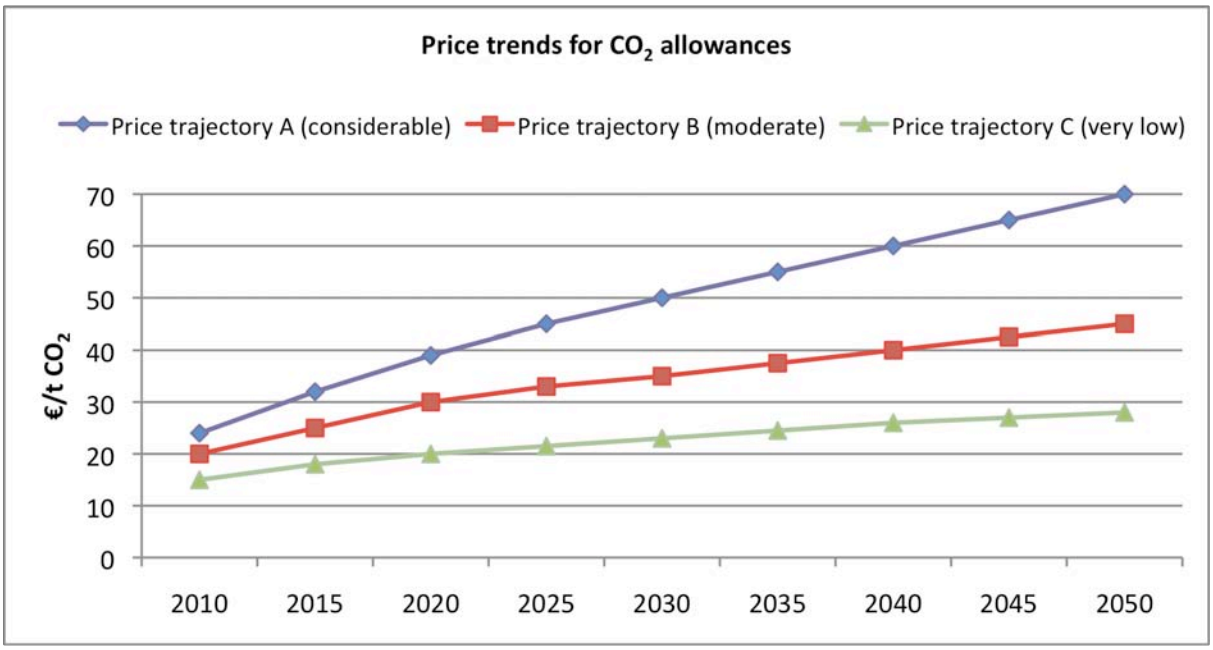

Fig. 9-2 Price trends for CO_2 allowances for trajectories A, B and C

Source: BMU 2008a

The cost burden caused by allowances is passed on in the form of penalties on fossil fuels. Ideally, it is assumed that allowances will be sold to the highest bidders, i.e. that an effective allowance trade comprising all energy consumers will be in place by 2012 (BMU 2008a). The forecast for future fuel prices *including* the impact of this CO_2 penalty is shown in Fig. 9-3. Here, the scenarios of fossil fuel prices are used proportionately to the prices of CO_2 emissions (for example, A/A = considerable increase in both fossil fuel prices *and* a considerable increase in the CO_2 penalty).

[72] Allowances currently cost around € 12.80/t CO_2 (as of: 22 January 2010).

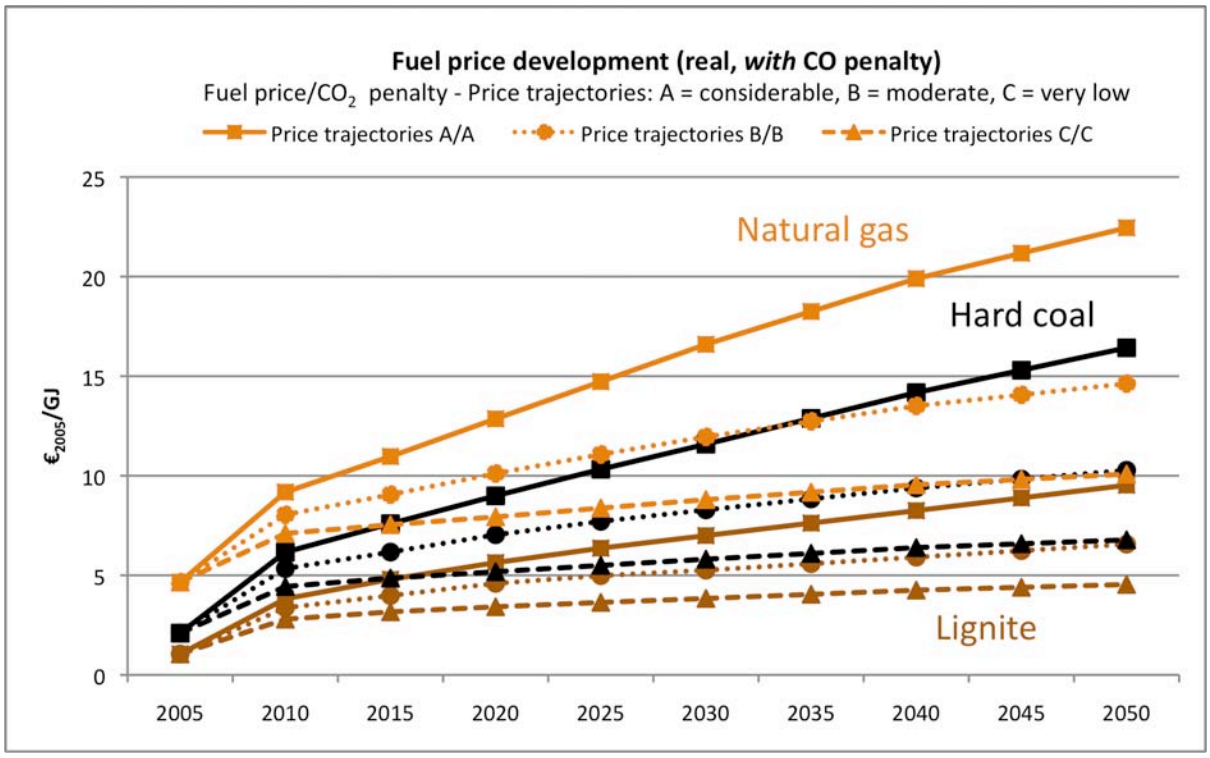

Fig. 9-3 Price trends for natural gas, hard coal and lignite at power plant for trajectories A/A, B/B and C/C (with CO_2 penalty)

Source: Based on BMU 2008a

Unlike in Fig. 9-1, there is a particularly steep increase in the cost of lignite and a slight rise in natural gas prices. This is due to the very high level of CO_2 emissions from lignite and the relatively low emissions from natural gas. Despite the relatively high CO_2 emissions from hard coal, the price rise caused by the scarcity of resources dominates the trend. This "CO_2 price sensitivity" can be clearly seen in the following Fig. 9-4, which also considers "mixed" scenarios.

- In **combination "A/C"**, a high fossil fuel price (price trajectory A), but only a low increase in CO_2 emissions (price trajectory C) is expected. This appears to be plausible because with price increases of this magnitude, a considerable drop in consumption is to be expected. This could lead to a surplus of CO_2 allowances, even in the event of a continued shortage of CO_2 allowances.
- Conversely, **combination "C/A"** signifies a slight increase in fossil fuel prices (price trajectory C), but a high increase in CO_2 prices (price trajectory A). This also appears to be plausible. This is because a decline in energy management activities with virtually static prices compared to the current fluctuations can no longer be assumed. The effect of this would be a constant rise in CO_2 prices in line with a continued shortage of allowances.

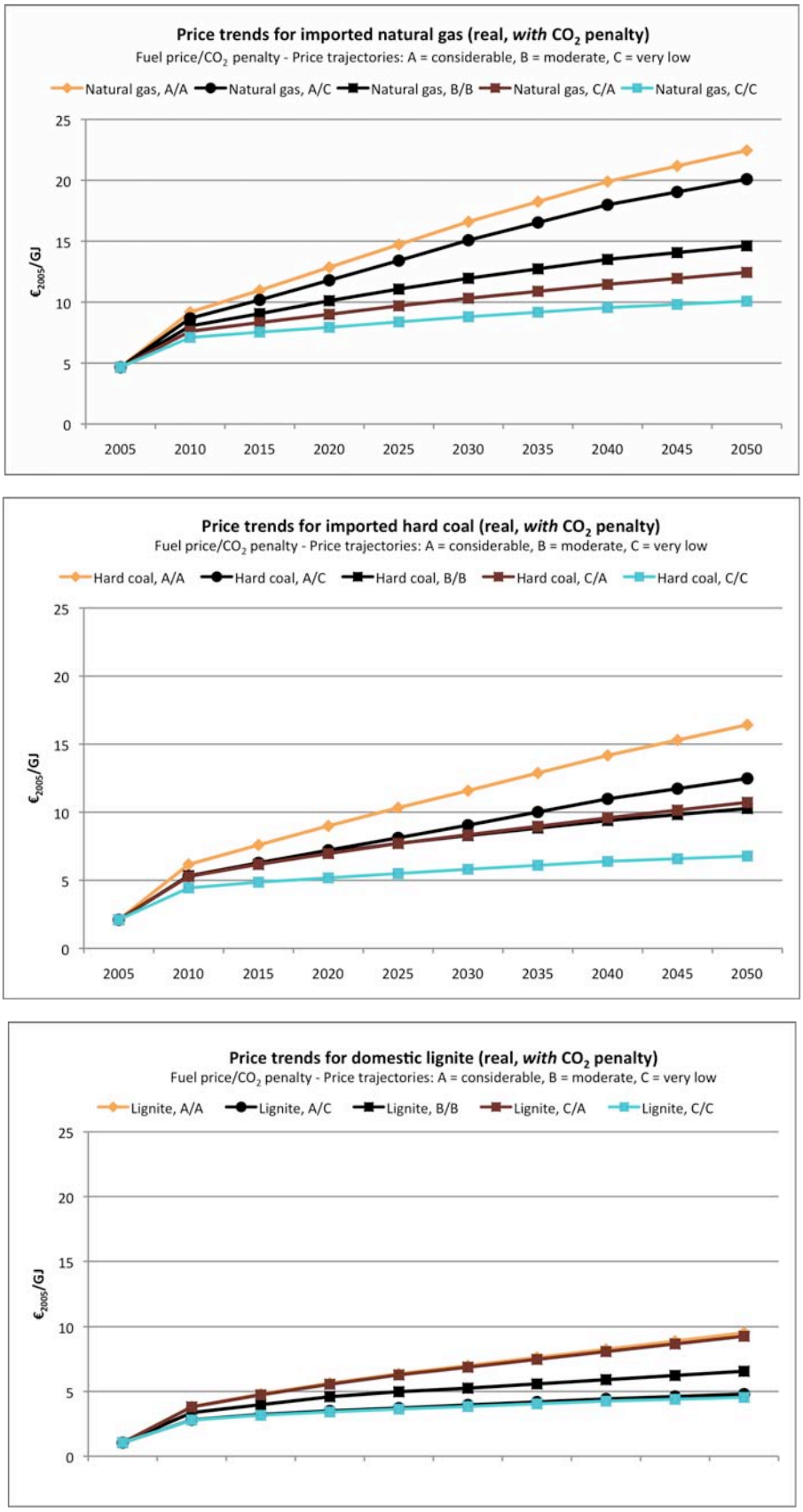

Fig. 9-4 Price trends for natural gas, hard coal and lignite at power plant for trajectories A/A, A/C, B/B, C/A and C/C (with CO_2 penalty)

Source: Based on BMU 2008a

Fig. 9-4 clearly shows that with natural gas, the scarcity of resources is responsible for the inflation, and that CO_2 prices have only a minor impact. Conversely, lignite is highly sensitive to CO_2 fluctuations, due to the relatively constant price for its extraction and the high CO_2 emissions. The scarcity of resources is also the main influence with hard coal, albeit not to the same extent as with natural gas. For natural gas and hard coal, these two combinations limit the ranges generated (upwards and downwards); for lignite they reverse the ratio, since only the second inflater (CO_2 prices) is relevant here: scenario C/A is on a par with high price scenario A/A, and scenario A/C with low price scenario C/C.

9.1.2 Cost assumptions and other parameters of CCS power plants and their reference power plants

Fossil fuel-fired power plants *without* CCS

The electricity generating costs of a fossil fuel-fired power plant are calculated using the formula

$$EGC = \frac{Inv \cdot af + C_{O\&M}}{capacity} + C_{fuel}$$

where

$$af = \frac{I \cdot (1+I)^n}{(1+I)^n - 1}$$

and

EGC	= electricity generating costs, [EGC] = EUR/kWh$_{el}$
Inv	= specific investment expenditure, [K_{inv}] = EUR/kW$_{el}$
af	= annuity factor, [af] = %/a
I	= real interest rate, [interest] = %
n	= depreciation period, [n] = a
$C_{O\&M}$	= specific operating and maintenance costs, [$C_{O\&M}$] = EUR/kW$_{el}$
C_{fuel}	= specific fuel costs (including CO_2 penalty), [C_{Fuel}] = EUR/kWh$_{el}$
capacity	= full load hours, [operating life] = h/a

All cost data in this report refer to 2005.

- **Investment expenditure**: The total amount invested is allocated to individual years on an annuity basis. Both the expected real interest rate and the depreciation period are included in the annuity formula. In this study, a 6 per cent per annum (real) interest rate and a 25-year depreciation period are assumed, producing an annuity factor of af = 7.8 per cent per annum. The expenditure for one year is therefore related to a kilowatt hour,

using the number of annual full load hours. The investment expenditure for newly built power plants is taken from (BMU 2008a)[73].

- **Operating and maintenance costs**: These costs describe the auxiliary and operating materials required, as well as annual maintenance costs. They are also allocated using the number of annual full load hours. The data is taken from the RECCS study.
- **Fuel costs:** The fuel costs were already determined in Section 9.1.1. Since there they apply to primary energy (EUR/GJ_{th}), they are converted to electricity generated (EUR/kWh_{el}) via the average power plant efficiency.
- **CO_2 penalty:** The cost of CO_2 allowances (EUR/t CO_2) is allocated to the primary energy via the calorific value of the energy source (GJ_{th}/t). This was already added to the fuel costs in Section 9.1.1.
- **Full load hours:** Both the investment expenditure and the operating and maintenance costs are allocated to a kilowatt hour generated via the number of annual full load hours (see below).

Fossil fuel-fired power plants *with* CCS

A penalty is imposed on the investment expenditure and operating and maintenance costs to calculate the electricity generating costs of *CCS power plants*. The figure for the lower degree of utilisation is also included in the fuel costs. Finally, a penalty is imposed for the transport of CO_2 and storage costs. However, usage fees for storage sites ("storage fee"), as called for by several federal states and (SRU 2009a), have yet to be included. Tab. 9-1 provides an overview of all assumptions for CCS power plants and their reference power plants.

The penalties on the investment expenditure are adopted more or less directly from the RECCS study. This seems justifiable because no commercial power plant has been built in the past three years, just various pilot and demonstration plants. The data from the original study are based on an extensive analysis of the literature, and the values used in it are converted into euros. Data was supplied for 2020 and 2040. The year 2020 was assumed to be the earliest time when commercial CCS power plants would be ready for operation. For this reason, this data describes "market-ready" power plants. The data referring to 2040 describes "mature" CCS power plants that have benefited from a learning curve. For this, the cost reductions derived in RECCS are based on learning rates according to (Rubin 2004) (reduction of typical CCS components by 11 to 13 per cent with a doubling of installed capacity).

Besides the additional expenditure, the degrees of utilisation and the anticipated reductions due to CO_2 capture are taken directly from the RECCS study. The assumed degrees of utilisation represent a situation in 2020 (projected on to 2040) for newly built power plants, and therefore already assume a considerably improved conversion compared with the current situation.

73 The degrees of utilisation of lignite steam power plants were slightly higher (closing at 50 instead of 47.5 per cent in 2050). This is because, according to information provided by companies, the future use of pre-dried lignite, which is considerably more efficient from the overall efficiency perspective, will become standard practice.

Finally, the costs for compression, transport and storage are also adopted. For the 200 km transportation distances typically covered in Germany, 0.20 ct/kWh$_{el}$ was set for gas-fired and 0.40 ct/kWh$_{el}$ for coal-fired power plants, and each reduced by 10 per cent for the "2040" projection.

Tab. 9-1 Expenses, costs and other parameters of "market-ready" CCS power plants (2020), "mature" CCS power plants (2040) and their reference power plants (2020)

		Natural gas NGCC		**Hard coal steam**		**Hard coal IGCC**		**Lignite steam**	
		2020	**2040**	**2020**	**2040**	**2020**	**2040**	**2020**	**2040**
A) Without CO_2 capture									
Degree of utilisation	%	60.0	62.0	49.0	52.0	50.0	54.0	46.0	49
Investment	€/kW$_{el}$	400	400	950	900	1,300	1,100	1,100	1,050
Operation, maintenance	€/kW$_{el}$,a	34.1	32	48.3	45	53	49	56	52.5
CO_2 emissions, direct	g/kWh$_{el}$	337	326	690	650	676	626	880	827
B) With CO_2 capture									
Degree of utilisation	%	51.0	55.0	40.0	44.0	42.0	46.0	34	39
Reduction of degree of utilisation	*% points*	*9*	*7*	*9*	*8*	*8*	*8*	*12*	*10*
Investment	€/kW$_{el}$	900	750	1,750	1,600	2,000	1,700	2,030	1,870
Difference in investment	*€/kW$_{el}$*	*500*	*350*	*800*	*700*	*700*	*600*	*930*	*820*
Operation, maintenance	€/kW$_{el}$,a	54	50	80	74	85	78	94	86
Difference in operation, maintenance	*€/kW$_{el}$,a*	*20.1*	*18*	*31.7*	*29*	*32*	*29*	*38*	*33.5*
Compression, transport and storage	ct/kWh$_{el}$	0.20	0.18	0.40	0.36	0.40	0.36	0.40	0.36
Capture rate	%	88	92	88	90	88	92	88	90
Additional use of fuel	%	18	13	23	18	19	17	35	26
CO_2 emissions, direct	g/kWh$_{el}$	48	29	101	77	97	59	143	104
CO_2 emissions, avoided	g/kWh$_{el}$	289	297	589	573	579	567	737	723

Source: RECCS study (WI et al. 2007), expanded

Number of full load hours

Both investment expenditure and operating and maintenance costs are allocated to a kilowatt hour generated via the number of annual full load hours. The usage capacity of power plants therefore emerges as a central parameter. While in the RECCS study it was assumed to be constant at 7,000 h/a, continually decreasing operating hours are used in this case. The scenario CCS-EE/KWK presented in Chapter 10 is used as the basis for this study. It is based on the current energy policy objectives of the Federation which are, in summary, the considerable expansion of renewable energies in the electricity sector, much greater efficiency and a high proportion of combined heat and power. In the study, it suggests that this will lead to not only the eventual phasing-out of nuclear power, but also to a considerable reduction in the usage capacity of fossil base load power plants. As shown in Tab. 10-2, the full load hours decrease from 5,616 h/a in 2010 to 3,589 h/a in 2050. The graph in Fig. 9-5 below also shows this course of development.

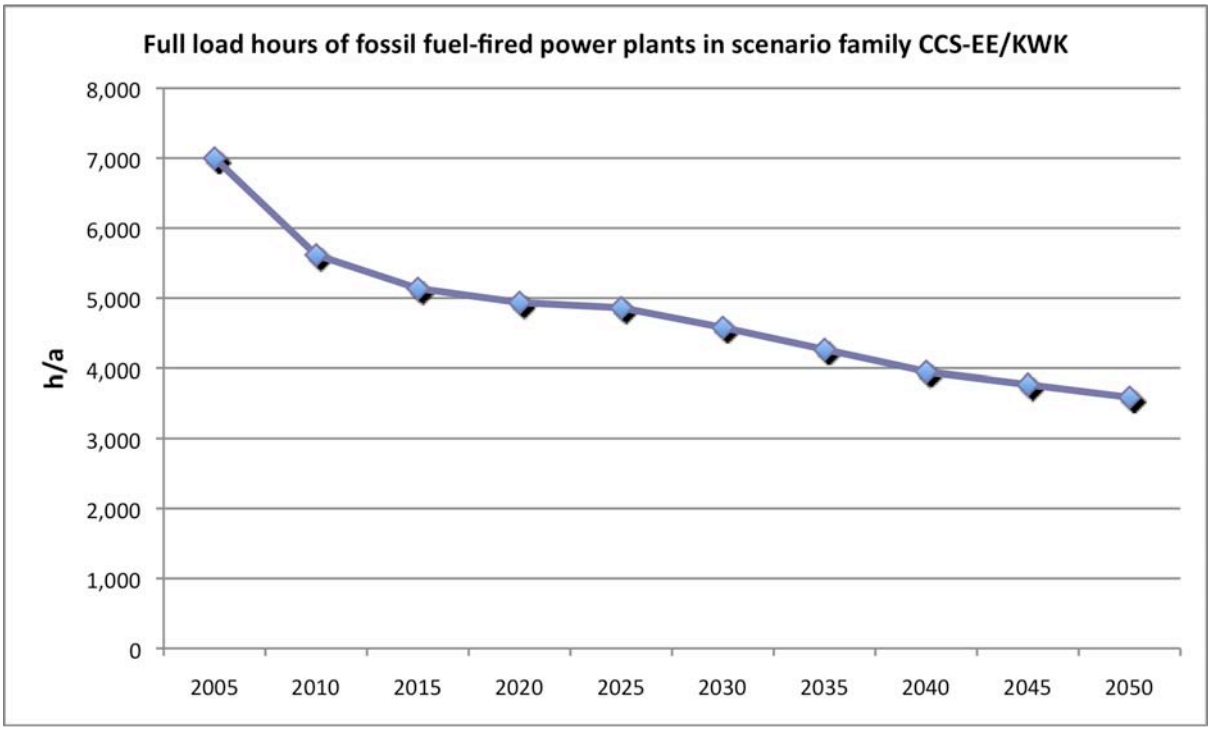

Fig. 9-5 Decline in the full load hours of fossil fuel-fired power plants in the scenario family CCS-EE/KWK (zero point is suppressed)

Source: Authors' design based on calculations in Chapter 10

A 50 per cent reduction in the full load hours compared with the situation in 2000 leads to a two-fold increase in kilowatt hour-related investment expenditure and operating and maintenance costs in 2050. On the other hand, the electricity generating costs are dominated by the development of fuel prices and the CO_2 penalties, as will be seen in the following section. The assumption that the full load hours will decline therefore leads to only a slight increase in the total electricity generating costs by 2050.

9.1.3 Calculation of electricity generating costs for CCS power plants

The following graphs (and Tab. 13-2 in the Appendix) show the development of electricity generating costs using the example of two "moderate" scenario combinations:

- **Price scenario A/C**: considerable increase in fossil fuel prices / slight increase in prices for CO_2 penalties
- **Price scenario C/A**: very slight increase in fossil fuel prices / considerable increase in prices for CO_2 penalties.

As explained above, these two combinations illustrate realistic ratios of energy prices to CO_2 prices. Due to their different capital requirements and the CO_2 intensity of the fuels and their power plants, however, they have a different impact on the development of electricity generating costs.

In addition, the costs of non-CCS power plants are compared to the potential trends for CCS power plants. Natural gas (NGCC), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants are considered.

Price scenario A/C

Fig. 9-6 and Fig. 9-7 compare the composition of electricity generating costs for fossil fuel-fired power plants both with and without CCS in scenario A/C.

- **Power plants without CCS**

  With the exception of lignite, the electricity generating costs of fossil fuel-fired power plants are already largely determined by the cost of the fuel. Although natural gas power plants have the highest fuel costs, they involve low investment expenditure and, due to their lower CO_2 content, lower CO_2 costs. In comparison, hard coal-fired power plants have higher investment expenditure, but save on fuel and pay higher CO_2 penalties. Although lignite power plants have the lowest fuel costs (see above), they have higher CO_2 penalties due to their higher CO_2 emissions.

  The rising fuel and CO_2 costs are explained by the scenario assumptions. Conversely, investment expenditure and operating costs are assumed to fall initially, due to the installed capacity. In terms of the power output, however, they increase because the full load hours between 2010 and 2050 are halved (Fig. 9-6).

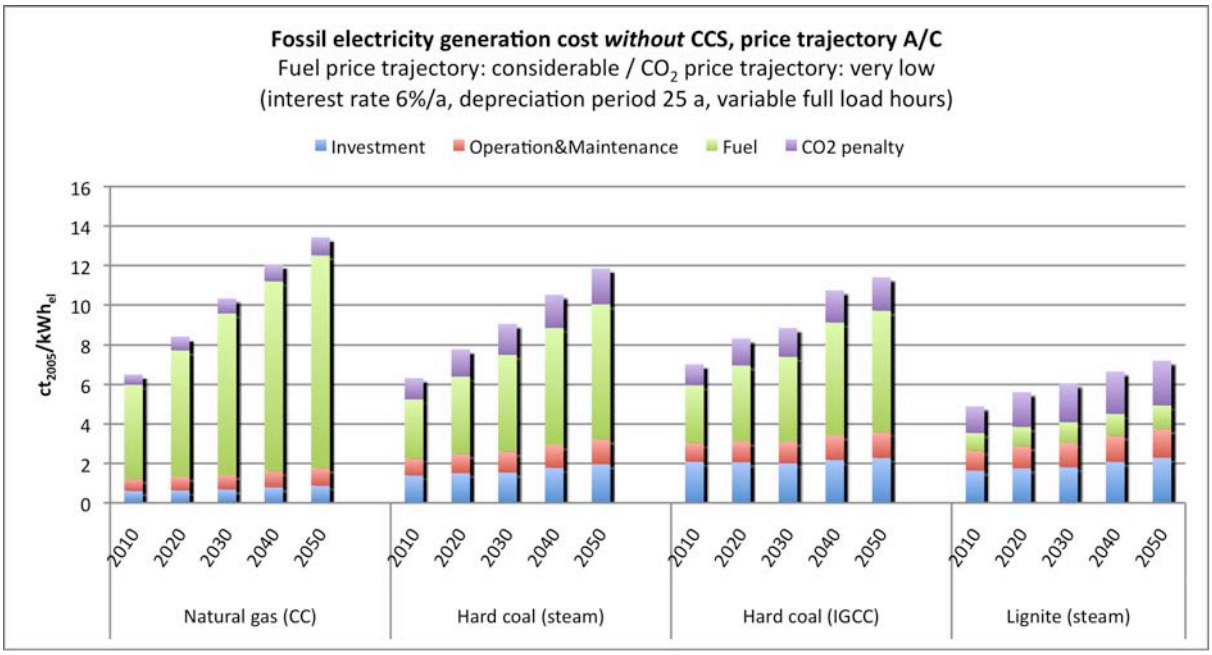

Fig. 9-6 Composition of electricity generating costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory A/C) (without CCS)

Source: Authors' design

- **Power plants with CCS**

  Different impacts are yielded when we calculate the electricity generating costs of CCS power plants: in general, the investment expenditure and fuel costs rise, whereas the CO_2 costs specifically (per kilowatt hour) decline. The latter, however, cannot be reduced to the same extent as the CO_2 capture rate, due to the additional consumption of primary energy. This means that, despite a capture rate of 88 to 92 per cent net, CO_2 emissions can be reduced by only 70 to 80 per cent (see Chapter 8).

The extent of this impact varies (Fig. 9-7): with natural gas-fired power plants with low investment expenditure but high fuel costs, the electricity generating costs in a high price scenario increase at a disproportionately high rate. With hard coal-fired power plants, the two components are balanced out, whereas with lignite-fired power plants even a high price scenario has only a minor impact. Due to the simultaneously assumed low CO_2 penalties, lignite continues to be favoured.

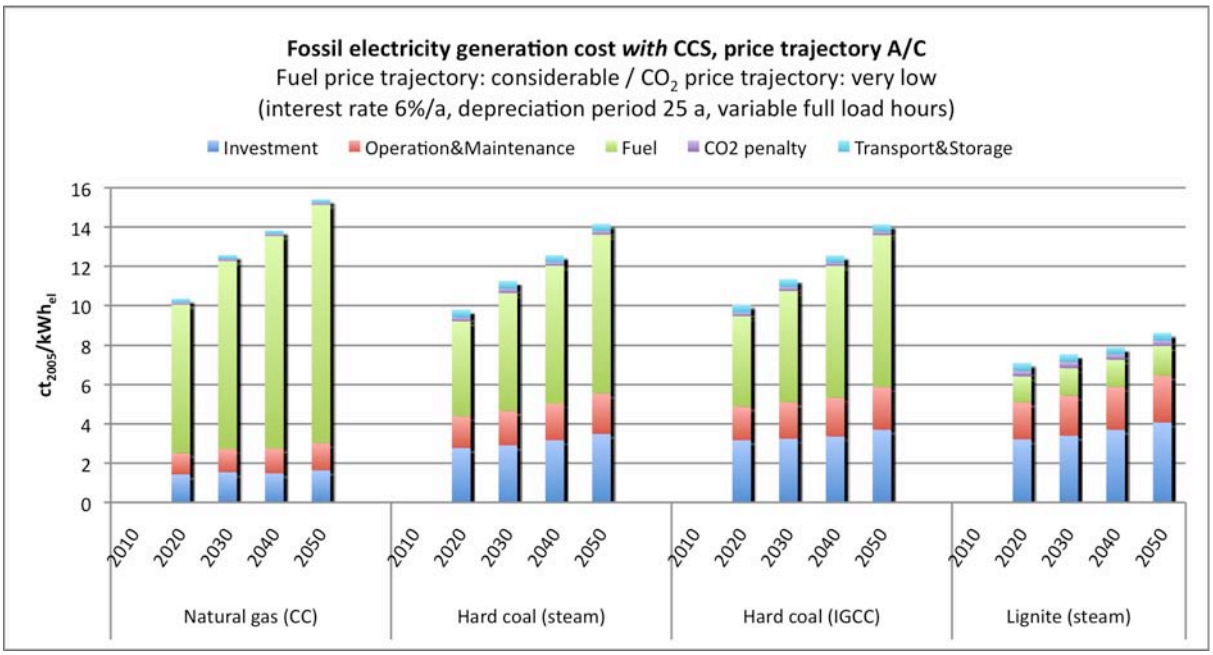

Fig. 9-7 Composition of electricity generating costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory A/C) (with CCS)

Source: Authors' design

If we now compare power plants *with* and *without* CCS, the following cost increases arise in the period from 2020 to 2050 due to the CCS chain (including transport and storage):

- Natural gas (NGCC): between 1.95 and 2.24 ct/kWh$_{el}$
- Hard coal (steam): between 2.02 and 2.22 ct/kWh$_{el}$
- Hard coal (IGCC): between 1.73 and 2.73 ct/kWh$_{el}$
- Lignite (steam): between 1.24 and 1.50 ct/kWh$_{el}$

Tab. 9-2 shows the differential costs and resulting CO_2 avoidance costs for 2020 and 2040.

Tab. 9-2 Differential costs of electricity generating costs and CO_2 avoidance costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory A/C) (with/without CCS)

		Natural gas NGCC		Hard coal steam		Hard coal IGCC		Lignite steam	
		2020	2040	2020	2040	2020	2040	2020	2040
A) Without CO_2 capture									
Electricity generating costs	ct/kWh$_{el}$	8.40	12.05	7.78	10.52	8.32	10.74	5.62	6.66
CO_2 emissions, direct	g/kWh$_{el}$	337	326	690	650	676	626	880	827
B) With CO_2 capture									
Electricity generating costs	ct/kWh$_{el}$	10.35	13.83	9.80	12.57	10.05	12.56	7.11	7.90
Difference in cost	ct/kWh$_{el}$	1.95	1.78	2.02	2.04	1.73	1.82	1.49	1.24
CO_2 emissions, direct	g/kWh$_{el}$	48	29	101	77	97	59	143	104
CO_2 emissions, avoided	g/kWh$_{el}$	289	297	589	573	579	567	737	723
CO_2 avoidance costs	€/t CO_2	67	63	34	36	30	33	20	17

Source: Authors' design

Price scenario C/A:

In contrast to the above scenario, Fig. 9-8 and Fig. 9-9 compare the elements of electricity generating costs in the case of very low energy prices, but high CO_2 penalties.

- **Power plants without CCS**

  Fuel costs continue to strongly influence natural gas power plants, whereas coal-fired power plants are dominated by CO_2 costs. With lignite power plants, in particular, CO_2 costs comprise at least half of the electricity generating costs. In accordance with the scenario assumptions, the fuel costs are considerably lower throughout than in the A/C scenario.

- **Power plants with CCS**

  The situation of CCS power plants in scenario C/A contrasts with that in scenario A/C (Fig. 9-9). CO_2 emissions are reduced as sharply as those in scenario A/C. However, due to the high CO_2 penalties there is a considerable reduction in the electricity generating costs for CCS power plants. On the other hand, the energy costs rise only slightly because of the low price scenario. Although they are generally higher than for power plants without CCS, due to the high efficiency losses, the decrease in CO_2 costs are increasingly less able to compensate for this beyond 2020.

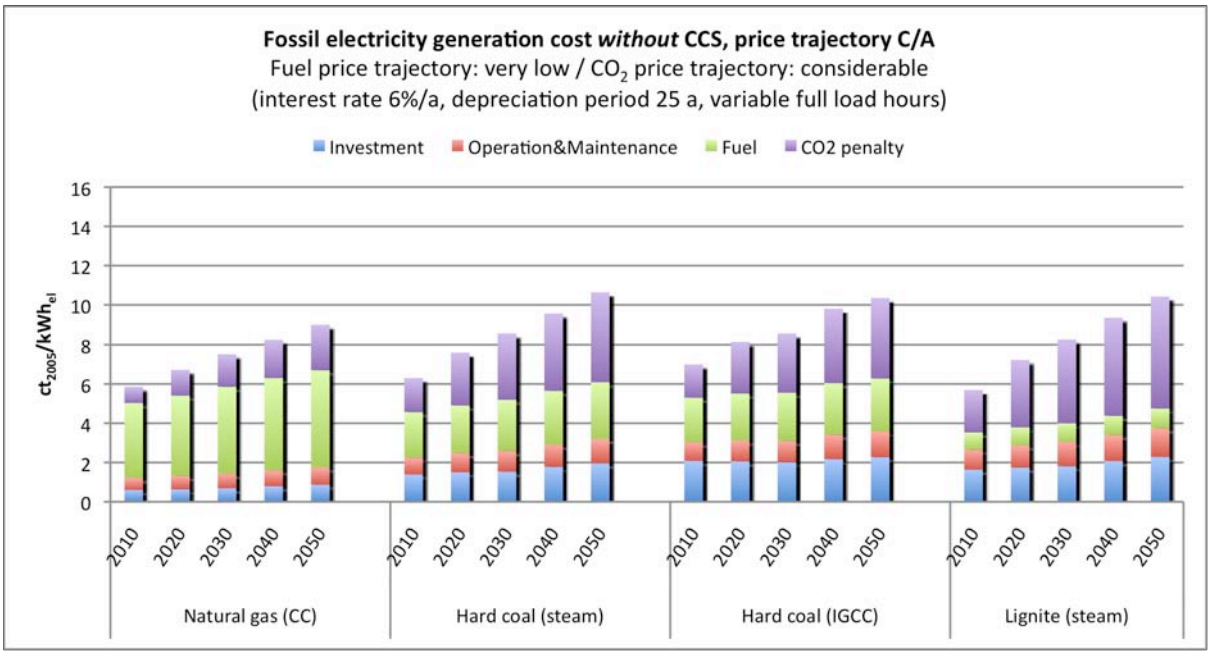

Fig. 9-8 Composition of electricity generating costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory C/A) (without CCS)

Source: Authors' design

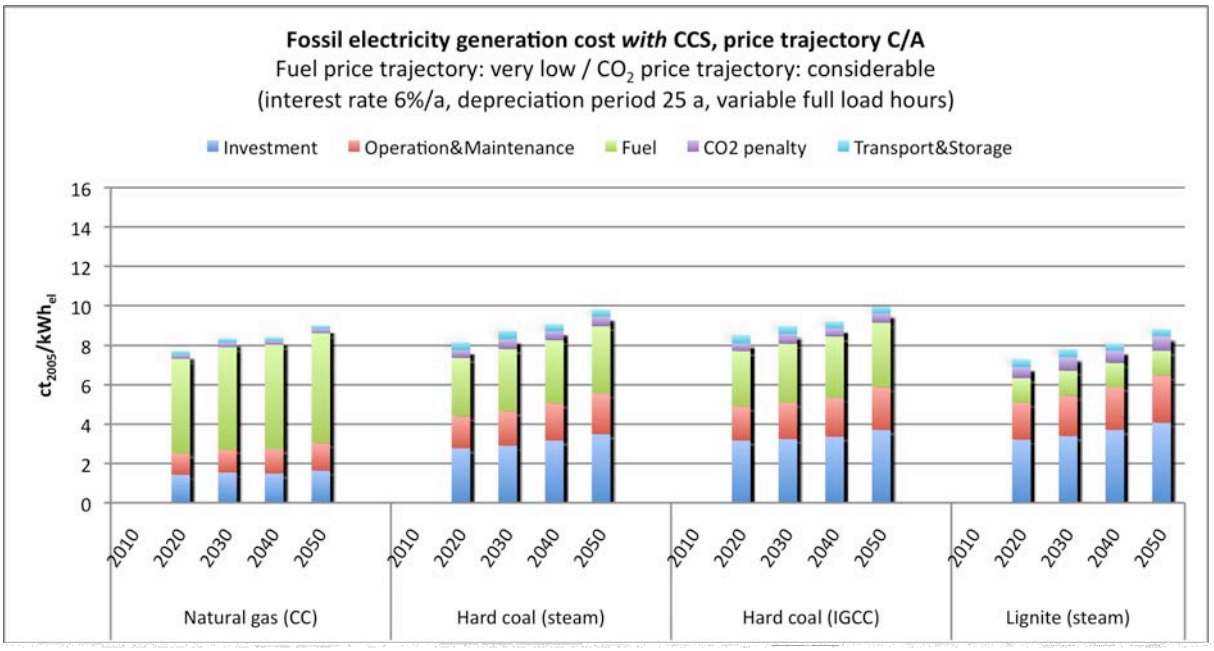

Fig. 9-9 Composition of electricity generating costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory C/A) (with CCS)

Source: Authors' design

This leads to a gradual alignment of the costs for plants with and without CCS, ultimately making CCS power plants cheaper than their reference plants. As is shown by the negative differential costs in Fig. 9-12, this process begins shortly after 2020 for lignite, between 2030

and 2040 for hard coal, and shortly after 2040 for natural gas. In 2050, lignite power plants with CCS have a considerable advantage (1.6 ct/kWh$_{el}$) over the reference variant. In summary, the CCS chain leads to the following cost increases or savings:

- Natural gas (NGCC): between 0.99 and 0 ct/kWh$_{el}$
- Hard coal (steam): between 0.57 and -0.85 ct/kWh$_{el}$
- Hard coal (IGCC): between 0.41 and -0.62 ct/kWh$_{el}$
- Lignite (steam): between 0.07 and -1.62 ct/kWh$_{el}$

Tab. 9-3, in turn, shows the differential costs and resulting CO_2 avoidance costs for 2020 and 2040.

Tab. 9-3 Differential costs of electricity generating costs and CO_2 avoidance costs (new plants) for natural gas (combined cycle), hard coal (steam), hard coal (IGCC) and lignite (steam) power plants (price trajectory C/A) (with/without CCS)

		Natural gas NGCC		Hard coal steam		Hard coal IGCC		Lignite steam	
		2020	2040	2020	2040	2020	2040	2020	2040
A) Without CO_2 capture									
Electricity generating costs	ct/kWh$_{el}$	6.72	8.25	7.6	9.56	8.15	9.81	7.23	9.34
CO_2 emissions, direct	g/kWh$_{el}$	337	326	690	650	676	626	880	827
B) With CO_2 capture									
Electricity generating costs	ct/kWh$_{el}$	7.71	8.40	8.17	8.71	8.50	9.19	7.3	8.8
Difference in cost	ct/kWh$_{el}$	0.99	0.15	0.57	-0.51	0.35	-0.62	0.07	-1.52
CO_2 emissions, direct	g/kWh$_{el}$	48	29	101	77	97	59	143	104
CO_2 emissions, avoided	g/kWh$_{el}$	289	297	589	573	579	567	737	723
CO_2 avoidance costs	€/t CO_2	34	5	10	-9	6	-11	1	-17

Source: Authors' design

9.1.4 Electricity generating costs of renewable energies

The electricity generating costs of CCS power plants are compared with renewable energies that generate power. This is a climate protection option that, unlike CCS, has already shown significant success in Germany. In 2007, for example, the share of renewables in electricity generation in Germany was 14.2 per cent, leading to the avoidance of 66 million tonnes of CO_2[74] (UBA 2009b). The question is, however, how this development will progress in the future, and whether renewable energies represent a real alternative to CCS in terms of cost. To resolve this, we need to consider their long-term development, rather than the actual situation; otherwise distorted results would be produced.

The cost trend of renewable energies is taken from the Lead Study 2009 (BMU 2009a) (see Tab. 13-3 in the Appendix). In that study, technology-specific learning effects were illustrated using learning curves,[75] developed using knowledge gained from global developments over

[74] In 2008, the share was already 15.1 per cent; it is expected to reach 16 per cent in 2009.

[75] An introduction to learning curves and examples from the power generation sector can be found in Juninger et al. 2008, McDonald and Schrattenholzer 2001 and IEA 2000.

the last decades. As a result of this study, it was found that it had been possible to reduce the cost of generating power from onshore wind turbines and photovoltaic plants by around one third between 1985 and 2005 (BMU 2009a). A similarly rapid cost degression is expected for offshore wind power stations. Their electricity generating costs are currently around 16.5 ct/kWh$_{el}$, and could fall to 5 to 6 ct/kWh$_{el}$ in the long term. According to (BMU 2008a), other significant cost regressions are expected for photovoltaics, geothermal energy and technologies for exploiting biomass. With the latter two sources, electricity generating costs are reduced further by increasing heat credits, if the waste heat is used in combined heat and power plants. A reverse trend was factored in to fuel prices for the use of biomass.

For evidence from the past, empirically determined learning rates were estimated to be somewhere between 10 and 25 per cent; for future development up to 2050, learning rates are estimated to be between 5 and 12 per cent: photovoltaics 10 per cent, biomass 5 per cent, solar thermal power plants 11.5 per cent and wind 9 per cent. These estimates are based on an ambitious global dynamic market growth of renewable energies, resulting in a proliferation of installed capacity. Fig. 9-10 shows the development of electricity generating costs for newly built plants based on these assumptions.

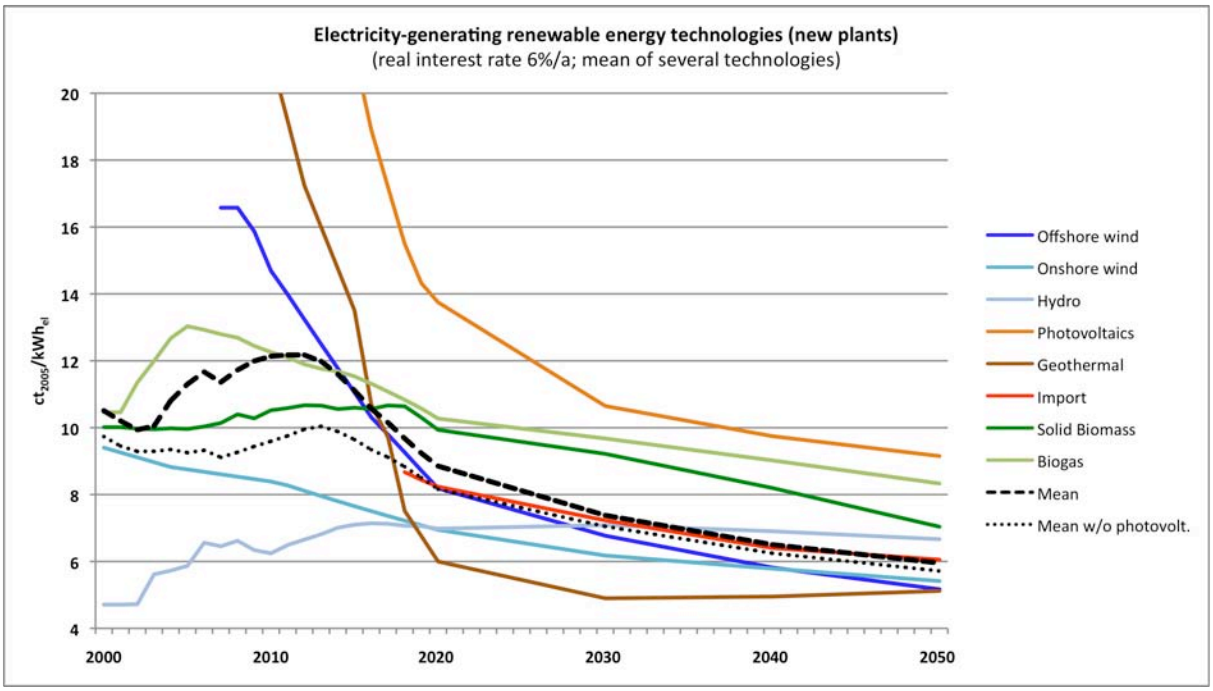

Fig. 9-10 Future cost trend of electricity-generating renewable energy technologies (new plants) and the mean of the whole mix of renewable energies (with/without photovoltaics; zero point is suppressed)

Source: Based on BMU 2009a

In the long term, electricity generating costs averaging 7 ct/kWh$_{el}$ will be achieved; the individual technologies will range from 5.1 to 9.1 ct/kWh$_{el}$. The greatest cost reduction takes place between 2010 and 2020. It then slows down up to 2030, after which the learning potential is only very low for most technologies.

9.1.5 Cost comparison of CCS power plants and renewable energies

Developing the previous two sections, we will now proceed to compare the cost curves for fossil fuel-fired CCS power plants with selected renewable energies. The economic perspectives of both options will then be discussed in the context of energy supply in Germany. The following energy technologies are chosen from Fig. 9-10 for the comparison:

- representative mix of new plants
- representative mix of new plants excluding photovoltaics
- offshore wind power stations
- Solar thermal power plants are also likely to play a major role in Germany in the medium to long term (in the Lead Study 2008, power plants from the European electricity supply grid are expected to constitute around 15 per cent of the total in 2050). As Fig. 9-10 shows, however, the cost curve of future solar thermal power plants from 2035 is more or less identical to the representative mix of renewable energies. For this reason, this technology is not presented in the following comparisons, keeping the figures as simple as possible.

Fig. 9-11 gives a general overview of all the cost trends; Fig. 9-12 presents the results for each individual technology (natural gas, hard coal steam power plants and lignite steam power plants).

One main difference between fossil fuel-fired power plants and renewable energies is initially that the cost trend of renewables is dependent only on technological factors and the assumed learning curves (based on assumed market volumes). In contrast, the future electricity costs from fossil fuel-fired power plants will be determined mainly by the price trend of fuels and the strength of climate policy (expressed in CO_2 prices). This is most certainly the case for CCS power plants which, due to their 35 per cent additional demand for fuel, is heavily dependent on future increases in fuel prices. Conversely, the costs of protecting the climate are considerably reduced by CO_2 capture.

Scenarios A/C and C/A, described above, are used again for the following comparisons:

- **Price scenario A/C**: considerable increase in fossil fuel prices / slight increase in prices for CO_2 penalties
- **Price scenario C/A**: very slight increase in fossil fuel prices / considerable increase in prices for CO_2 penalties.

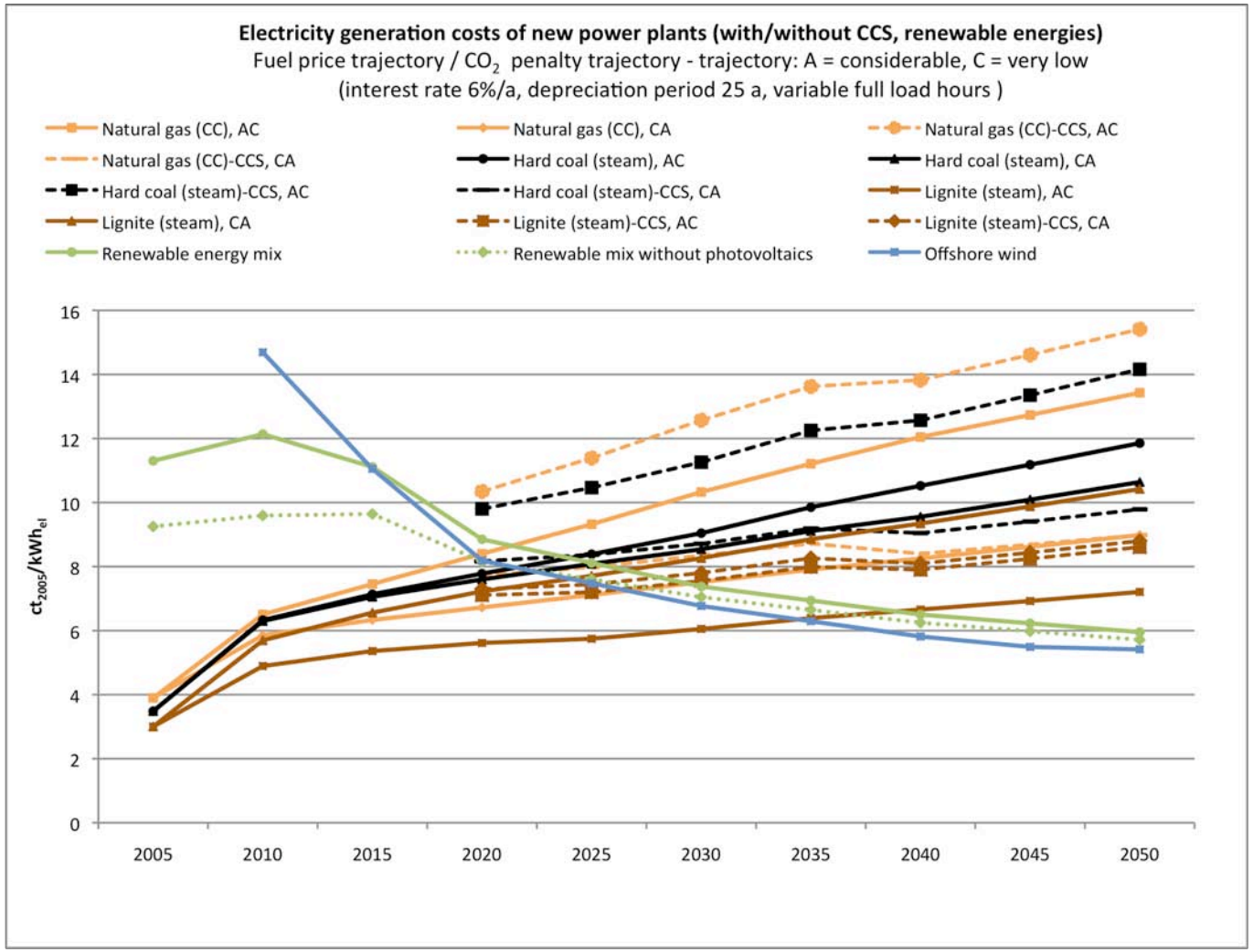

Fig. 9-11 Development of future electricity generating costs (new plants) for renewable energies and fossil fuel-fired power plants (with/without CCS) for price trajectories A/C and C/A (CCS from 2020, including transport and storage)

Source: Authors' design

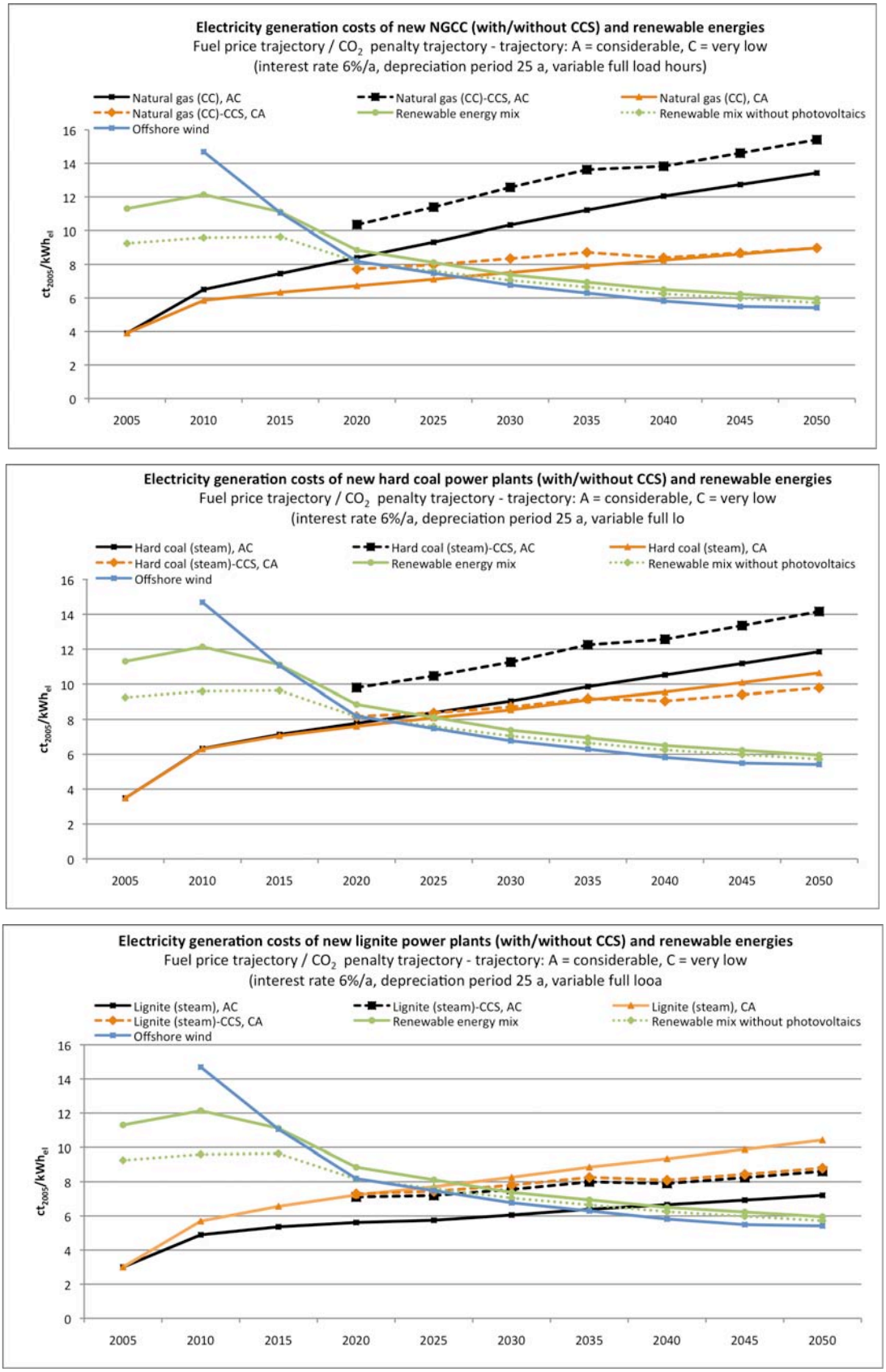

Fig. 9-12 Development of future electricity generating costs (new plants) for renewable energies and fossil fuel-fired power plants (with/without CCS) for price trajectories A/C and C/A – detailed portrayal of natural gas (combined cycle), hard coal and lignite steam power plants

Source: Authors' design

Power plants *without* CCS compared with renewable energies

Fig. 9-11 initially shows that, with the selected price assumptions, electricity generating costs for fossil fuel-fired power plants *without CCS* will also be more expensive than renewable energies in Germany in the short to medium term. In the event of a *very low* increase in fossil fuel prices (scenario C/A), electricity from hard coal will already be more expensive than electricity from renewable energies in the period 2020-2025; natural gas will follow between 2025 and 2030. Lignite will also no longer be cost-effective by 2025 (due to the high CO_2 penalties).

If a *considerable increase* in fuel prices is assumed (scenario A/C), natural gas-fired power plants will be more expensive than renewable energies from as early as around 2020. The development of hard coal is the same as above in that period. Lignite-fired power plants, on the other hand, will only be cheaper sources of production than renewable energies up to sometime between 2035 and 2040 (due to the currently low CO_2 prices).

Power plants *with* CCS compared with renewable energies

If CO_2 separation and storage are included, two opposite effects are observed, as shown in the previous section. If fuel prices rise *considerably* (scenario A/C), the electricity generating costs of fossil fuel-fired CCS power plants will increase by between 1.50 and 2 ct/kWh$_{el}$. This will have the effect of renewable energies being cost-effective considerably earlier than had been anticipated: natural gas- and hard coal-fired power plants from 2020, lignite from 2025 (offshore wind) or 2030 (renewables mix).

In the case of *very low* energy prices (scenario C/A), the situation is reversed: whereas the generating costs of CCS power plants are initially (in 2020) 0.07 to 1 ct/kWh$_{el}$ higher than without CCS, the difference in cost is increasingly reduced and is reversed in 2050 to a reduction of between 0 and 1.6 ct/kWh$_{el}$. In other words, CCS power plants will increasingly be able to produce cheaper electricity than their reference plants due, in particular, to the high CO_2 penalties for the plants without CO_2 capture. Nevertheless, fuel costs also rise in this scenario which, together with the ever-declining operational lifetimes, lead to a steady increase in electricity generating costs. On the other hand, renewable energies can further exploit their advantage and continually reduce their costs, albeit at a slower rate due to the deceleration in learning rates. All these aspects mean that fossil fuel-fired CCS power plants will produce electricity more expensively than renewable energies from 2020 in this scenario, too. The one exception is lignite-fired power plants, where cost parity is only achieved from 2025. The high CO_2 penalty, which cannot be fully compensated by CO_2 capture, has a particularly high impact in this case.

Later deployment of CCS (2025, 2030)

All calculations in this chapter are based on the assumption that CCS technology will be commercially viable by 2020. If it turns out that it cannot be realised, the cost increases that the figures show for 2020 with the planned introduction of CCS would be postponed to later years (2025 or 2030). This would mean, however, that renewable energies would be able to produce energy more cheaply in both the low and high price scenario as early as when CCS is first introduced. On the other hand, renewable energies would then also have more scope for flexibility if their cost reduction (based on the assumption of learning rates) was also delayed by five to ten years.

9.2 An aside: Reflections on the suitable cost term and scope of the system – definition of break-even point

9.2.1 Suitability of the annuity approach

In the present study, we follow the usual method for determining the break-even point of the costs of generating electricity using two competing power generation technologies, as described, for example, in (Nitsch 2009). In this example, a comparison was made between regenerative energy technologies on the one hand and power generation technologies using fossil fuels, coupled with downstream CCS, on the other.

This usual procedure is based on the financial mathematical principle of "annuity". Annuity is one of three possible financial mathematical methods for transforming a cost curve over time into a one-dimensional cost value. A break-even point can only be determined after a procedure such as this. What is helpful about choosing the "annuity" procedure is that it is also incorporated into the widely used unit "costs of producing electricity (including transport) per kilowatt hour" (ct/kWh$_{el}$). Determining power generation costs on an annuity basis is generally used to ascertain a fixed price for the product over the lifetime of the generating plant, guaranteeing a financial mathematical economic balance of expenditure and revenue for this lifespan. It does not appear, however, that the annuity is appropriate for accurately calculating the break-even point of competing technologies.

Bearing this in mind, we should reflect on the real reasons for determining the break-even point. At first sight, there is some doubt about the financial mathematical parameter, used in its standard form, since annuity is not the criterion generally applied when it comes to making investment decisions, where the *capital value criterion* is usually applied.

The objective pursued by determining the break-even point is to ascertain the point at which there is a change in decision-making from one power generation technology to another. It is the investors in power plants alone who create this switch, and yet they do not necessarily follow the "annuity" approach. The pertinent question is, therefore, at what point will power plant investors consider renewable energy technologies to be preferable over more traditional power generation technology, i.e. that based on fossil fuels. Or, to be more precise: since there is a gap of several years between calculations and the start of construction, or initial operation on the basis of a different calculation, the crucial question is when this change with respect to the construction of new power plants will take place. This point in time can be very different to that determined in the usual way of using average costs on an annuity basis. The direction of this deviation is not generally predictable, nor can it be predicted whether, quantitatively, it will be high. That would require an in-depth exploration of the issue outlined here, which was not part of the remit of the present study.

9.2.2 Suitability of the section of the system selected to determine costs: the relevance of stock market orientation in electricity price building versus CO_2 allowance prices

If it is agreed that the objective of determining the break-even point of "production costs" is to establish at which point the technology change will actually take place, and if it is assumed that this point in time is obtained from the calculations of power plant investors, it follows that

there must also be an examination of whether the parameters within the section of the system that influences production costs in the calculation correspond with that section, regardless of the financial mathematical approach selected for processing the chosen cost parameters. By choosing correctly, they will accurately and relevantly influence the calculation, and not distort it.

There is some doubt as to whether the section of the system chosen in the standard form of the result is correct. The reason for this is the debate about the influence of the prices for CO_2 permits on the relevant production costs in investors' calculations. This debate revealed, or reminded us, that it can no longer be generally, or readily, assumed that price formation is oriented towards production costs in the given structure of the electricity market and with the prevailing practices of (market-related) pricing. This stock market-led approach to electricity pricing causes complex interrelationships to dominate, creating a situation that can be difficult for the layperson to interpret. The method of mark-up pricing for estimating costs would be more universally understood. What's more, if the newly established price formation mechanism is considered or anticipated by power plant investors in their calculations, it could transpire that certain parameters included by definition in the production costs are in fact viewed as items in transit and are, therefore, no longer relevant to the decision-making process.

The fact is that as long as older coal-fired power plants represent the marginal cost for power plants in the German power market most of the time and, in this capacity, determine the wholesale prices for electricity, the risk of cost ineffectiveness for new coal-fired power plants due to rising or volatile prices of CO_2 allowances is negligible. As a result, it is overlooked in investors' calculations. An increase in CO_2 prices caused by higher emissions or a change in political circumstances, or the risk of volatile CO_2 prices leads to higher costs for new power plants when considering matters in the traditional (isolated) way (see Section 9.1.3). However, as was widely expected, the higher costs for the power plants that set the wholesale market price (that are less efficient and therefore involve higher CO_2 costs) are reflected in the electricity price building at the stock exchange – this leads to a higher electricity revenue and compensates the (increased) CO_2 costs. The price for CO_2 permits is consequently considered to be an in-transit item, and therefore does not influence power plant investors' calculations (in Germany). This is how interrelations are represented on the basis of a suitable, non-restricted calculation (according to Prognos et al. 2009).

The significance of shifting the perspective of a calculation, as suggested, is that the prices of CO_2 permits would have to be deleted from the calculation and the (real) *break-even point* would be reached eventually. However, a correction to the calculation by neutralising the influence of the prices of CO_2 permits should only be made if the prices for fossil fuels and those of CO_2 permits are each viewed independently. It may be the case that many market participants (still) see it like this. The present study, however, refrained from adopting this viewpoint for the relevant cases. Here, using the definition of scenarios A/C and C/A, it was assumed that CO_2 prices do influence fuel prices, and, indeed, generally in the opposite direction.

These observations show that since even the method of the prevailing calculation can be defective and is (therefore) open to interpretation, any substantial elaboration of this point

requires broad dialogue with power plant investors regarding their calculations. This, too, requires a detailed exploration that goes beyond the scope of the present study.

9.2.3 The impact of CCS power plants on determining price in an electricity stock market-oriented calculation

With an electricity stock market-based approach to electricity pricing, the (purchasing) costs (for electricity consumers) are not equal to the sum of the production costs (of electricity producers) plus a mark-up. The figures are not even similar because it is not a case of neglecting profit in the sense of a risk premium. From the perspective of power plant investors, it is also the case that the anticipated return on a power plant, when conceived as a commodity with a redeemable price and full load period of usage, is as an integral of the deployment of the power plant or the feed-in of its capacity, evaluated using the stock market price of the product at that time. Consequently, the deployment of power plants, and hence their revenue, is crucially dependent on the relationship between the marginal costs of the options of production used, i.e. their "merit order" at a particular time. The expected return on a power plant is thus determined to a lesser extent by its average costs, as in the customary method of determining break-even point, and to a greater extent by its marginal costs. In addition, it is context-sensitive, i.e. dependent on the relationship of its own marginal costs with the marginal costs of competing power plants. This competitive relationship ultimately determines the realised capacity utilisation. It is therefore a major step forward that these relationships have been described in essence (Sensfuß 2009a,b), (Sensfuß and Ragwitz 2006, 2008), (Sensfuß et al. 2008).

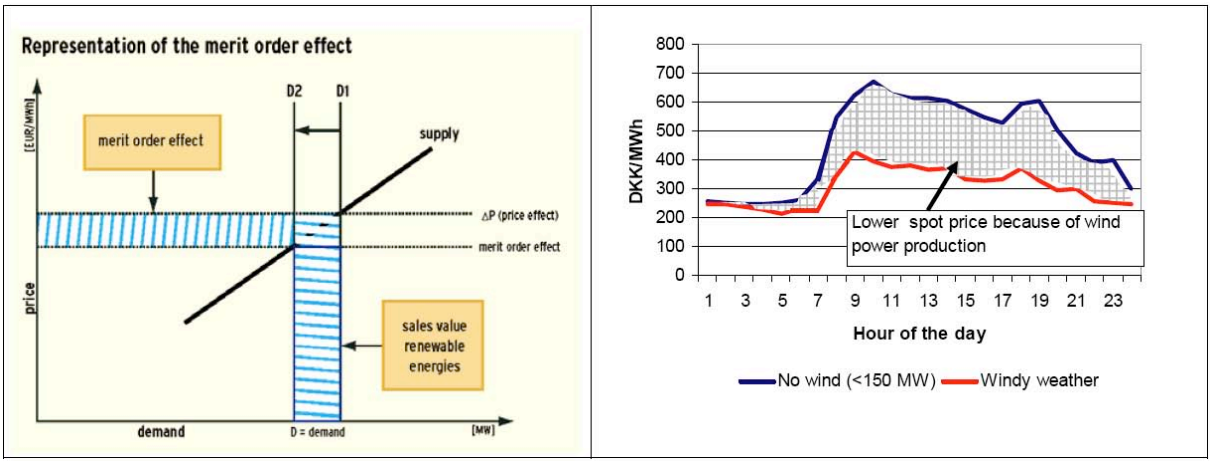

Fig. 9-13 Schematic diagram: the marginal costs effect of renewable energies influences the average generating costs of electricity according to their usage characteristics

Source: Sensfuß and Ragwitz 2007 (left) and Morthorst 2007 (right)

The principle of this new method of determining costs, even if in another part of the system, is presented in Fig. 9-13. Using this diagram, the authors have derived that "for 2006 … the sum of the market value and the merit order effect ... [is] higher than the entire Renewable Energy Law allowance," (Sensfuß and Ragwitz 2007:14). They therefore prove empirically that, despite their higher average production costs, renewable energy technologies have led to lower electricity prices (average costs for electricity consumers) than would have been the case at a power plant site without renewables, i.e. at a power plant site with lower average

costs. Hence the change in the average production costs of power generation technologies cannot be applied linearly to the change in average production costs that affect electricity consumers' bills, and yet the latter cost term is the more economically significant of the two.

For the present study, it is important to start with these results and then to develop them a step further. Now we will turn to how this situation changes when, on the fossil power generation technology side, CCS is installed downstream (particularly to coal-fired power plants) and viewed as a new type of power plant, and when renewable energy beyond wind is on the market. The crucial element is how the *marginal costs* change on both sides. Power plant operators consider marginal costs to be variable, i.e. they do not apply when the operational power plant is not in use. In general, these are (mainly) the costs for the energy source used:

- For *renewable energy technologies,* the following principally applies: provided that the source of energy is free, the "energy costs", and therefore marginal costs, equal zero. The validity of this principle is reduced if storage processes play a role, i.e. in the case of hydropower (with the exception of run-of-river power stations) or also in the case of solar-thermal electricity generation with night or peak sharing.
- For *fossil power generation technologies,* the fuel costs are generally considered to be the marginal costs. As a surcharge, the costs for CO_2 permits that may (or may not) be incurred, must be added to this, as measured by their (volatile) stock market price. The question is now how adding downstream CCS changes this marginal calculation.

This has already been touched upon for coal-fired power plants with downstream CCS. However, the form of this investigation was such that it would be inappropriate to transfer the results to the present discussion (Prognos 2009). In their model, which is stylised, the areas of fossil fuel-fired power plants and renewable energy technologies were isolated from one another – cost-driven substitutional competition between the two types of electricity generation is not an option in the model. A substitution is only permitted within the area of fossil fuel-based electricity generation, the share of which is set beforehand (the assumption was that nuclear power was excluded). The only remaining options for a substitution are therefore natural gas (with imported, high-price natural gas, the price of which rose even during the research) and coal-fired CCS power plants (it is assumed that the price of coal is declining). Electricity generation from renewable energies, on the other hand, was exogenously given as a share (which therefore contradicts the growth targets set by politicians).

The result of the investigation is that a considerable expansion of coal-fired power plants are equipped with CO_2 capture, and are therefore more expensive, leading to a *reduction* in the wholesale prices of electricity by 17 per cent (€ 32 billion) or 22 per cent (€ 66 billion) compared to the case "without CCS." In other words, this is once again a change of sign in the relationship of costs between the two variants and further proof of the relevance of Sensfuß's perspective. This result is based here on a change in the price-determining type of power plant in the merit order between natural gas power plants and coal-fired power plants. *Without* the CCS option (for coal), natural gas (in the purely fossil part of the power plant fleet) would, in wide areas of application, replace coal which, due to CO_2 charges, would have higher marginal costs in future. *With* CO_2 capture, the marginal costs of coal-fired power plants remain low – with its downstream "chemical factory", the CCS plant is extremely capital-intensive, and therefore marginal cost-extensive. The downstream CCS plant therefore impedes the change to natural gas power plants, with higher marginal costs, in many areas.

As a result, we reach another different angle, depending on the cost term used. If the principle of mark-up pricing applies with regard to costs for CO_2 permits, they increase the production costs for fossil-based power generation technology *with* CCS compared to that *without* CCS, and change the competitive situation vis-à-vis renewable energy power generation technologies in favour of the latter. If, on the other hand, cost-setting with merit order applies, they decrease the average production costs for fossil-based power generation technology *with* CCS compared to that *without* CCS, and therefore change the competitive situation vis-à-vis renewable energy power generation technologies at the expense of the latter.

The crucial question, however – which of the two climate protection options (CCS or renewable energies) has the greatest impact on the overall decreasing prices of electricity – was not examined. Since the marginal costs of renewable energies tend towards zero and therefore remain lower than those of CCS power plants, they should also be able to offer a crucial advantage here, too.

9.3 Conclusions from the economic analysis

After successfully demonstrating the entire CCS chain (the capture, transport and, in particular, storage of CO_2), according to our calculations, electricity generating costs from CCS power plants of between 7.30 and 10.35 ct/kWh$_{el}$ (at power plant) can be achieved by 2020 (assumed real interest rate 6 per cent per annum). The price range depends on both the technology taken into consideration and the price trends of fuel and CO_2 allowances up to 2020. The usage fees for storage sites (“storage fee”), as called for by several federal states and the German Advisory Council on the Environment, have not yet been included.

Two scenarios were considered: very low increasing fuel costs with high CO_2 penalties (scenario C/A) and considerably rising energy costs that cause a surplus of and, therefore, decreasing CO_2 penalties (scenario A/C). In the latter case, considered to be the more realistic scenario, CO_2 avoidance costs in 2020 of € 68/t CO_2 (natural gas), € 43/t CO_2 (hard coal) and € 20/t CO_2 (lignite) are produced.

Depending on further price trends, the long-term cost projections of CCS range from 8.10 to 13.80 ct/kWh$_{el}$ in 2040 and from 8.80 to 15.40 ct/kWh$_{el}$ in 2050. Lignite steam power plants are in the lower region, hard coal power plants (steam and gasification) are in the medium to high range, and natural gas in the top range. Despite increasing running costs, CO_2 avoidance costs decrease due to learning effects by 2040 to € 61/t CO_2 (natural gas), € 36/t CO_2 (hard coal) and €17/t CO_2 (lignite). With the exception of lignite, therefore, they are still a long way from achieving the costs of around € 20/t CO_2 to which the power industry aspires.

The average electricity generating costs of renewable energies are presently around 12 ct/kWh$_{el}$, assuming a representative mix (also calculated at a real interest rate of 6 per cent per annum). When photovoltaics are excluded from the mix, the average costs amount to around 10 ct/kWh$_{el}$. If they continue to be launched at a similar speed as before, average electricity generating costs of approximately 8.8 ct/kWh$_{el}$ (including photovoltaics) and 8.2 ct/kWh$_{el}$ (excluding photovoltaics) can be achieved by 2020. A sustained global increase in market penetration and learning effects give reasons to expect further significant cost degressions for renewable energies over time. By 2050, therefore, the level of costs in the investigated characteristic mix could be around 8.8 ct/kWh$_{el.}$ Technologies such as offshore

wind power or geothermal energy could achieve electricity costs of around 5 ct/kWh$_{el}$ if their learning curve continues to be used for the further expansion of global markets.

If the dynamics of the expansion of renewables in the electricity sector remains high, as assumed in the scenario family CCS-EE/KWK (Chapter 10), individual renewable energy technologies (offshore and onshore wind power, solar thermal power plants) will be able to compete with CCS power plants as early as in 2020, which is considered to be the potential starting point for CCS power plants. The average mix is partially competitive even now. If fuel prices increase *considerably*, the generating costs of CCS-based natural gas- and hard coal-fired power plants will be higher from 2020 than for renewable energies. Lignite-fired CCS power plants will follow from 2025 (offshore wind/solar thermal energy) and 2030 (mix of renewable energies). Even in the case of *very small* increases in energy prices, the additional costs incurred by CCS would be so high that renewable energies would remain competitive at the same time as in the high price scenario. The high CO_2 penalty, which cannot be fully compensated by CO_2 capture, has a particularly powerful impact on lignite.

The whole calculation is based on the assumption that CCS technology will be commercially viable by 2020. If CCS is not made available until a later stage, the increases in costs previously assumed for the year 2020 during the introduction of CCS would be postponed to later years (2025 or 2030). This would mean, however, that renewable energies would be able to produce energy more cheaply in both the low and high price scenario as early as when CCS is first introduced On the other hand, renewable energies would then also have more room for manoeuvre if their cost reduction (based on the assumption of learning rates) was also delayed by five to ten years.

Banking analysts confirm the basic assertion of the calculations presented here. In its 2009 industry report on photovoltaics, for instance, the Landesbank Baden-Württemberg also modelled other options of CO_2 reduction using scenarios. Regarding CCS, they conclude that this technology is “not practicable on commercial and economic grounds, not even in Central Europe. Solar electricity generation is not more expensive than CCS (and much cheaper from 2020).” (LBBW 2009:6). It raises the question: “Which technology should be subsidised in future from taxpayers’ money: ‘cleaning’ conventional, fossil fuel-fired power plants, which have an expiration date, by CCS or supplying industrial society with solar electricity, which is arguably more sustainable.” (LBBW 2009:54).

According to the assumptions made, therefore, there is no compelling incentive from an economic perspective to favour CCS technologies over the further expansion of renewable energies for power generation. Further considerations show, however, that the issue of generating costs and the break-even point between CCS-based power plants and renewable energies are no longer the only decisive factors from the viewpoint of investors. Our calculation of the electricity costs on an annuity basis is not necessarily the calculation used by investors. The traditional mark-up method in electricity pricing, which enables additional investments, the higher fuel costs and an increasing price for CO_2 permits to be included in our calculation, has now been superseded by the stock market approach. This leads to effects such as the additional CO_2 costs being factored into the price, causing them to be considered as only an item in transit, meaning that they do not influence the calculations of power plant investors. In fact, the current price for electricity is determined by the stock market price, which, in turn, is dependent on the merit order of operational power plants. While research

has subsequently proved that renewable energies have led to a decrease in electricity prices, despite their currently higher capital expenditure (since their marginal costs are virtually zero, unlike with expensive natural gas), it remains to be seen how they will influence CCS-based power plants.

10 Systems-analytical assessment of CCS in national scenarios

10.1 Review of the scenarios in the RECCS study

In the RECCS study, three different scenarios were developed in order to analyse the role of CCS in the energy sector in comparison to renewable energies in Germany (WI et al. 2007, Chapter 14). These three scenarios will be mentioned below before proceeding to the new scenarios developed in this study. In all three scenarios, energy-related CO_2 emissions in Germany were reduced to 240 million tonnes per annum by 2050, which corresponds with an approximately 75% reduction compared with 1990 levels. The scenarios were based on the following assumptions:

- **CCS-MAX** as the main element of a climate protection strategy with “maximum use” of CCS technologies from 2020 within the framework of a development that otherwise largely follows current trends (relatively small mobilisation of efficiency potentials and limited implementation of the expansion potentials of renewables). According to the results of the scenario calculation, such a strategy runs into structural and capacity limits. The earliest date when CCS is expected to be ready for commercial implementation is 2020, which is too late for the current first wave of the power station replacement programme in Germany. This scenario would necessitate extremely rapid growth rates for CCS plants (new construction and retrofitting older power plants) between 2020 and 2050. It would not be possible to achieve the climate protection targets in 2050 with CCS alone. The transport sector would have to achieve additional reductions, necessitating the construction of a hydrogen infrastructure (based on coal gasification with CO_2 separation). By 2050, hydrogen would be the dominant form of energy, supplying 47 per cent of final demand.
- **CCS-BRIDGE** as “bridging technology” if, despite efficiency increases and renewables being implemented more consistently than in the business-as-usual conditions, major players in energy policy and management assume from the outset that these strategy elements will not suffice to achieve the “-80 per cent” target. Such a strategy would give CCS technology the chance to establish itself in the German power supply after 2020. For 2050, this results in a quite balanced mix of electricity from renewables (245 TWh/a), CCS electricity (146 TWh/a) and conventionally generated electricity from fossil fuels (150 TWh/a). However, this scenario is also unable to meet the climate protection targets in the electricity sector, although it is more successful than under CCS-MAX conditions. The requirements for introducing a hydrogen infrastructure in the transport sector are less extensive than in CCS-MAX, because the required contributions of CCS and hydrogen may still be relatively low up to 2030. Hydrogen would make up 29 per cent of energy sources in 2050. As in the CCS-MAX scenario, CCS-BRIDGE would also require a considerably larger supply of primary energy.
- **NaturschutzPlus** as a path with a vigorous and ecologically optimised expansion of renewables and across-the-board exploitation of energy efficiency potentials. This scenario was one of the forerunners of the Lead Scenarios subsequently published by the

BMU (BMU 2007, BMU 2008a, BMU 2009a). This scenario describes a development that gives a long-term perspective to the expansion of renewable energies, introduced by energy policy, and which increasingly combines it with growing contributions of a more efficient conversion (combined heat and power, CHP) and use of energy. The use of CCS technologies is not necessary for climate protection purposes; the scheduled phasing out of nuclear energy is adhered to. An expansion of CHP is an important characteristic of this scenario, which enables it to transfer the consumption of natural gas from the heating sector to the electricity sector, and even to continually reduce it from 2020.

The new scenario developed in this study incorporates elements from both CCS-MAX and NaturschutzPlus. As in the NaturschutzPlus scenario, it is assumed that energy management targets set by the German government, such as the expansion of renewables and CHP, will indeed be implemented. However, as in CCS-MAX, it is assumed that the necessary efficiency measures will only be implemented to a moderate extent. The varying use of CCS is envisaged for the remaining demand for electricity from fossil sources. This use is depicted in a “scenario family” **CCS-EE/KWK**, comprising six variants, based on the BMU’s Lead Scenario 2008.

10.2 Lead Scenario 2008 and definition of the CCS-relevant variant D

The Lead Scenario 2008 in (BMU 2008a) describes a scenario that shows how greenhouse gas emissions caused by the electricity, heat and transport sector in Germany can be reduced to around 20 per cent of the 1990 level by 2050. The *Zwischenziele der Bundesregierung* (Interim Targets of the German government) for 2020 are also portrayed in the Lead Scenario against the backdrop of this general objective. These interim targets are:

- to reduce CO_2 emissions to 35 to 40 per cent of 1990 levels,
- to double the 1990 rate of energy productivity,
- for renewables to make up 18 per cent of overall energy consumption (30 per cent of electricity)
- to considerably expand combined heat and power, as stipulated in the resolutions of the German government, applicable laws and EU Commission regulations;
- finally, to adhere to the legally determined phasing out of nuclear power.

The Lead Scenario describes the structural change of energy supply in Germany necessitated by these objectives.

Scenarios generally demonstrate the potential future developments of energy systems under the assumption that the conditions set for the scenario construction will come true, that set targets will be achieved and, moreover, that no unforeseeable events will occur that fundamentally change the whole system. However, it also makes sense to model missed targets or the non-fulfilment of desired conditions. The quantitative effect enables us to gain information on the significance of action taken or on the degree to which targets have been missed.

Missed targets with regard to the intended efficiency increases in all sectors were modelled in two variants D1 and D2 in (BMU 2008a). In scenario D2, a coal-oriented investment strat-

egy was additionally assumed in the power plant sector, which approximately represents energy suppliers' current plans. Combined with inadequate efficiency successes, the implementation of these plans would have dramatic effects on the desired path for reducing CO_2. In 2020, CO_2 emissions from the entire energy supply, at 743 million tonnes per annum, would be around 100 million tonnes per annum higher than those in the Lead Scenario 2008, which would be merely a 25 per cent reduction compared to 1990. By 2050, CO_2 emissions would only be reduced to approximately 400 million tonnes of CO_2 per annum, despite the same expansion of renewables as in the Lead Scenario 2008, i.e. twice the amount required to meet the "-80 per cent" target (see Fig. 10-1 for the course of D2). In this scenario, however, it must be borne in mind that the co-existence of a huge expansion of renewables and a respective plan to expand coal-fired power plants will lead to a continual reduction of the running time (full load hours) of coal-fired power plants (see below). For this reason, they may no longer be economically viable, even without CO_2 capture.

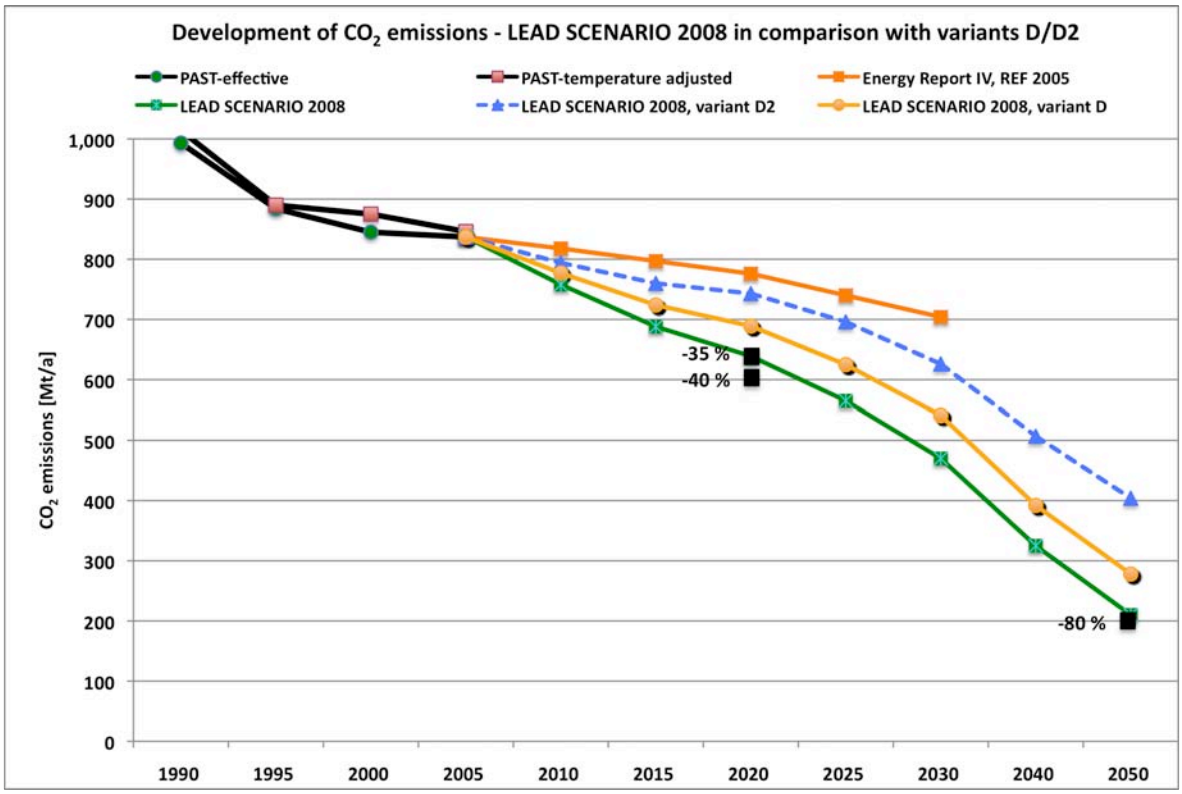

Fig. 10-1 Development of CO_2 emissions in the Lead Scenario 2008 and in variants D2 (coal-oriented) and D (plus reduced efficiency), comparison with the business-as-usual conditions of Energy Report IV and the reduction targets of the German government for 2020 and 2050

Source: BMU 2008a; EWI and Prognos 2005

The development outlined in scenario variants D1 and D2 can also be used to illustrate the impact of capturing and retaining carbon dioxide from power plants (CCS technology) and to monitor whether the climate protection targets can still be achieved or whether they should be approached in a different way. Unlike the considerations in (BMU 2008a), a scenario variant is developed in this study (variant D) that only takes missed targets and various investment strategies in the electricity sector into account to enable the impact of a varying degree of use of CCS technologies to be clearly portrayed. *In scenario D, therefore, the heat and transport sector is identical to that in the Lead Scenario 2008, and "only" considers the ef-*

fects of a less efficient use of electricity and the coal-oriented investment strategy for new power plants presented in variant D2. Due to the expansion of combined heat and power in the Lead Scenario 2008, a large number of combined heat and power plants will also need to be equipped with CO_2 capture technology. The expansion of renewables in all sectors also remains the same.

The resulting course of CO_2 emissions from the entire energy supply in variant D *without CCS measures* is also visible in Fig. 10-1. In 2020, CO_2 emissions will amount to 689 million tonnes of CO_2 per annum, a reduction of 30 per cent compared to 1990 levels. By 2050, emissions will fall to 278 million tonnes of CO_2 per annum, which corresponds to a 72 per cent reduction from the 1990 level. Unlike in the Lead Scenario 2008, this scenario shows the impact of higher electricity consumption and power plant construction geared more heavily towards coal.

We will now describe the key data of scenario D before we proceed to use these to define the variants of scenario CCS-EE/KWK.

10.3 Energy and emission-related key data of the model

The values presented in Tab. 10-1 are used to run the following model calculations, as previously used in the RECCS study. Although the assumed degrees of utilisation represent the situation in 2020 for new power plants, they assume a considerably improved situation compared to the current state. Since individual technologies (e.g. thermal power plant and IGCC) are not modelled in the scenario calculations, an average degree of utilisation is applied. The same utilisation loss is assumed for retrofitted CCS power plants and new power plants, despite the fact that retrofitted plants are unlikely to achieve the same level of efficiency as new power plants.

Tab. 10-1 Energy and emission-related key data of the model in 2020

	Unit	Lignite power plant mix	Hard coal power plant mix	Natural gas combined cycle power plant
A) Without CO_2 capture				
Degree of utilisation	%	47.5	49.5	60
CO_2 intensity fuel	g CO_2/MJ	112	92	56
	g CO_2/kWh	403	331	202
CO_2 intensity electricity	g CO_2/kWh_{el}	849	682	337
B) With CO_2 capture				
Degree of utilisation	%	36	41	51
Reduction	% points	11.5	8.5	9
Additional demand for primary energy	%	32	21	18
CO_2 intensity CCS electricity *before* capture	g CO_2/kWh_{el}	1,176	885	417
CO_2 capture rate	%	88	88	88
CO_2 captured	g CO_2/kWh_{el}	1,035	761	367
CO_2 intensity CCS electricity *after* capture	g CO_2/kWh_{el}	141	104	50

Source: Authors' design

Here, 88 per cent is taken as the CO_2 capture rate, the average value derived in the RECCS study. The quantities of CO_2 to be captured and the remaining emissions at the power plant are yielded from the capture rate and efficiency loss. Please note that, in this case, quantities *to be captured* are not identical to the *avoided* quantities of CO_2 because CO_2 emissions initially rise proportionately to higher consumption of primary energy.

10.4 Power plant-related key data of scenario D and the scenario family CCS-EE/KWK

The necessary construction of new fossil fuel-fired power plants up to 2050 can be determined from the decommissioning of existing power plants (including the phasing out of nuclear power), as assumed in (BMU 2008a), the future total gross demand for electricity and the assumed expansion of renewable energy plants. The resulting expansion of capacity from 2005 is shown in Tab. 10-2.

Development of the power plant mix

In scenario D, the need for new fossil fuel-fired power plants increases to a total of 47 GW up to 2040. After then, it decreases again slightly up to 2050 due to the further considerable expansion of renewable energies. Only large-scale power plants are affected by this reduction because the capacity of decentralised CHPP will steadily increase up to 2050. By 2050, all of the “old power plants” (power plants up to 2005) will have been replaced by new plants (maximum service life of 40 years for large-scale power plants). For this reason, the values in the column headed “2050” in Tab. 10-2 also correspond with the total capacity from power plants installed in this year (with the exception of larger hydro-electric power plants with longer service lives).

In scenario D, associated with a coal-oriented expansion strategy, almost 41 GW fossil fuel-fired power plants are in operation in 2050 which, in principle, could be fitted with CCS technologies. Of this amount, 24.7 GW are from hard coal-fired power stations (12.7 of which as CHPP), 9.3 GW from lignite-fired power stations (3.2 GW of which as CHPP) and 6.8 GW from natural gas power stations (4.8 GW as CHPP). These values lay the foundations for further investigations into the possibilities of using CCS technologies in the area of electricity.

The quantities of electricity that can be generated in these power plants (compare Tab. 10-2) are the result of the concurrence of all power-generating plants to meet the respective demand. *The significant expansion of renewables and the intended higher share of CHP will have an increasing impact on the utilisation period of fossil fuel-fired power plants because the base load operation will gradually decrease. Their efficiency will decrease from an average of 5,600 h/a in 2010 to 3,600 h/a in 2050.* This factor must be taken into account in economic analyses regarding CCS and the mode of operation, since CCS power plants require base load operation due to the chemical processes that occur during capture. An incompatibility is already visible between capital-intensive large-scale power plants, operated with the longest possible utilisation period, and a rapidly growing contribution of renewables to the future power supply. This conflict will intensify with CCS power plants. A power plant mix from the perspective of optimum CCS operation would therefore have a much smaller share of renewable energies than assumed in scenario D – derived from the Lead Scenario 2008 –

(such a power plant mix was portrayed in scenarios CCS-MAX and CCS-BRIDGE in the RECCS study).

In addition, a coal-oriented expansion strategy has an impact on the mix of renewable energies that can be used: in the NaturschutzPlus scenario, natural gas power plants, which could compensate fluctuating energies, such as wind power and photovoltaics, due to their flexible operation, are increasingly built. However, this is not possible on such a scale in scenario D. Since coal-fired power plants cannot be regulated as easily as natural gas power plants, base-loadable renewable energies, such as biomass, geothermal energy or solar thermal power plants (imported from southern Europe or north Africa), would mainly have to be used in this case.

Tab. 10-2 Construction of new fossil fuel-fired power plants from 2005, accessible capacity for CCS (large-scale power plants) and their electricity generation, comparison with expansion of renewable energies and their electricity generation in scenario D

	Unit	2010	2015	2020	2025	2030	2040	2050
Fossil fuel-fired power plants	GW_{el}	8.5	20.6	29.1	39.5	45.2	46.9	46.2
- Hard coal, other solid fuels	GW_{el}	4.6	12.7	16.7	22.3	25.2	26.0	24.7
- Lignite	GW_{el}	2.8	5.5	6.7	9.2	10.6	9.3	9.3
- Natural gas, oil	GW_{el}	1.1	2.4	5.7	8.0	9.4	11.6	12.2
Of which in combined heat and power generation	GW_{el}	4.0	9.7	14.0	19.2	24.1	30.3	34.2
- CHPP (coal, natural gas)	GW_{el}	1.4	5.0	7.4	10.6	13.6	17.8	20.9
- Small CHPP (natural gas, oil)	GW_{el}	0.5	0.8	1.4	2.6	3.8	4.9	5.4
Large-scale fossil fuel-fired power plants (STP, CHPP), suitable for CCS	**GW_{el}**	**8.0**	**19.8**	**27.7**	**36.9**	**41.5**	**42.0**	**40.8**
Electricity generation in new large-scale fossil fuel-fired power plants	TWh/a	45.0	101.6	136.5	178.4	195.9	176.0	146.4
For information only: capacity expansion renewable energies	GW_{el}	20.7	38.5	58.2	78.1	93.4	119.2	137.1
Electricity generation in renewable energy plants from 2005	TWh/a	45.3	85.6	136.3	200.0	255.9	367.1	457.5
Utilisation period of fossil fuel-fired power plants	h/a	5,616	5,137	4,936	4,861	4,579	3,951	3,589
STP = condensation power station; CHPP = combined heat and power plant								

Source: Authors' design

Definition of the CCS-EE/KWK scenario and its six sub-variants

The parameters presented in Section 10.3 are used for the energy and emissions-related balancing of CCS technologies in the following. For these calculations, it is assumed that CCS technologies will be available from 2020, i.e. that the first power plants with CCS will be built or retrofitted from 2021. A number of variants of the expansion of CCS capacity are considered to enable the potential range of impacts of CCS expansion to be illustrated. A differentiation is made between new power plants and retrofitted power plants commissioned between 2010 and 2020. The latter will be retrofitted 10 to 20 years after being put into operation. Although this approach exceeds the "retrofitting limit" which (McKinsey 2008) classifies

as when a power plant is 10 to 12 years old, it considers the fact that a very high "CCS capacity" would otherwise have to be installed within a short period (2030 to 2035).

A further differentiation is made between large-scale condensation power stations and combined heat and power plants, which generally have less capacity (Tab. 10-3). It is furthermore assumed that new fossil fuel-fired power plants built between 2005 and 2010 will be replaced by new CCS power plants at the end of their service life, i.e. between 2045 and 2050. The following six variants of the CCS-EE/KWK scenario are defined:

Tab. 10-3 Proportion of power plants equipped with CCS in the investigated variants of scenario CCS-EE/KWK

Scenario variants	New STP	Retrofitting STP	New CHPP	Retrofitting CHPP
1. Maximal – Theoretisch	100%	100%	100%	100%
2. Maximal – Realistisch	100%	65%	75%	35%
3. Maximal – Neu	100%	-	75%	-
4. Realistisch I	75%	40%	40%	20%
5. Realistisch I (only Kohle)	75%	40%	40%	20%
6. Realistisch II	50%	30%	30%	15%
STP = condensation power station; CHPP = combined heat and power plant				

Source: Authors' design

1. **Maximal – Theoretisch**: The share is systematically reduced, based on the theoretical upper limit, which assumes that all large-scale power plants fired by fossil fuel and combined heat and power plants will be fully equipped with CCS in 2050.
2. **Maximal – Realistisch**: It is initially assumed that combined heat and power plants, as condensation power stations, can only be equipped with CCS to a small extent. On the one hand, they usually have a relatively low capacity of around 200 MW_{el}. On the other hand, they are often located in cities, which means there is little space available for capture plants and transport infrastructure. In addition, the acceptance of CCS plants is likely to be much lower in cities than for large-scale power plants on the edge of towns.
3. **Maximal – Neu**: One sub-variant considers only new plants because retrofitting is disadvantageous compared to new constructions, from an energy and economic perspective.
4. **Realistisch I**: Not all sites are suitable for being connected to CO_2 pipelines. Since the potential CO_2 storage locations are situated in northern Germany (see Fig. 7-8), all power plants south of the Main are simply excluded from CCS operation. (McKinsey (2008) does not include the southern German power plants in their European-wide cluster either, due to a lack of storage possibilities, see Fig. 10-8.) Approximately 75 per cent of the power plant capacity from fossil fuels installed in Germany then remains. Roughly this share is combined with the factors in variant 2.
5. **Realistisch I – only Kohle**: One sub-variant considers only coal-fired power plants.
6. **Realistisch II**: In the last variant, the potential share of power plants north of the Main that may be viable for CCS is reduced by another third compared to variant 4. This (fixed

amount) accounts for the fact that individual power plants may not be able to be connected to a transport network or that not all power plants can be equipped with CCS for capacity and economic reasons.

10.5 Results of the variant calculation in CCS-EE/KWK

The overall result with regard to the reduction in CO_2 is illustrated in Fig. 10-2. It first becomes apparent that the considerable contribution electricity generation makes to CO_2 emissions today, amounting to around 310 million tonnes of CO_2 per annum, will generally decline significantly due to the substantial growth of renewable energies. In the Lead Scenario 2008, emissions from the entire electricity sector will decline to 28 million tonnes of CO_2 per annum in 2050, since by then there will only be very little power-generation capacity from fossil fuels, mainly in the form of CHP plants and natural gas condensation power stations.

In scenario D (without CCS), the CO_2 emissions from the electricity sector are reduced to 96 million tonnes of CO_2 per annum. They account for 35 per cent of the then existing CO_2 emissions, 278 million tonnes of CO_2 per annum. CCS can be employed in this segment. Since the average capture rates in CCS power plants are assumed to be 88 per cent, the remaining emissions in scenario D can be reduced by a maximum of 85 million tonnes of CO_2 per annum to approximately 11 million tonnes per annum, the theoretical upper limit. In this theoretical border case, the remaining CO_2 emissions would fall below the value of CO_2 emissions in the Lead Scenario 2008.

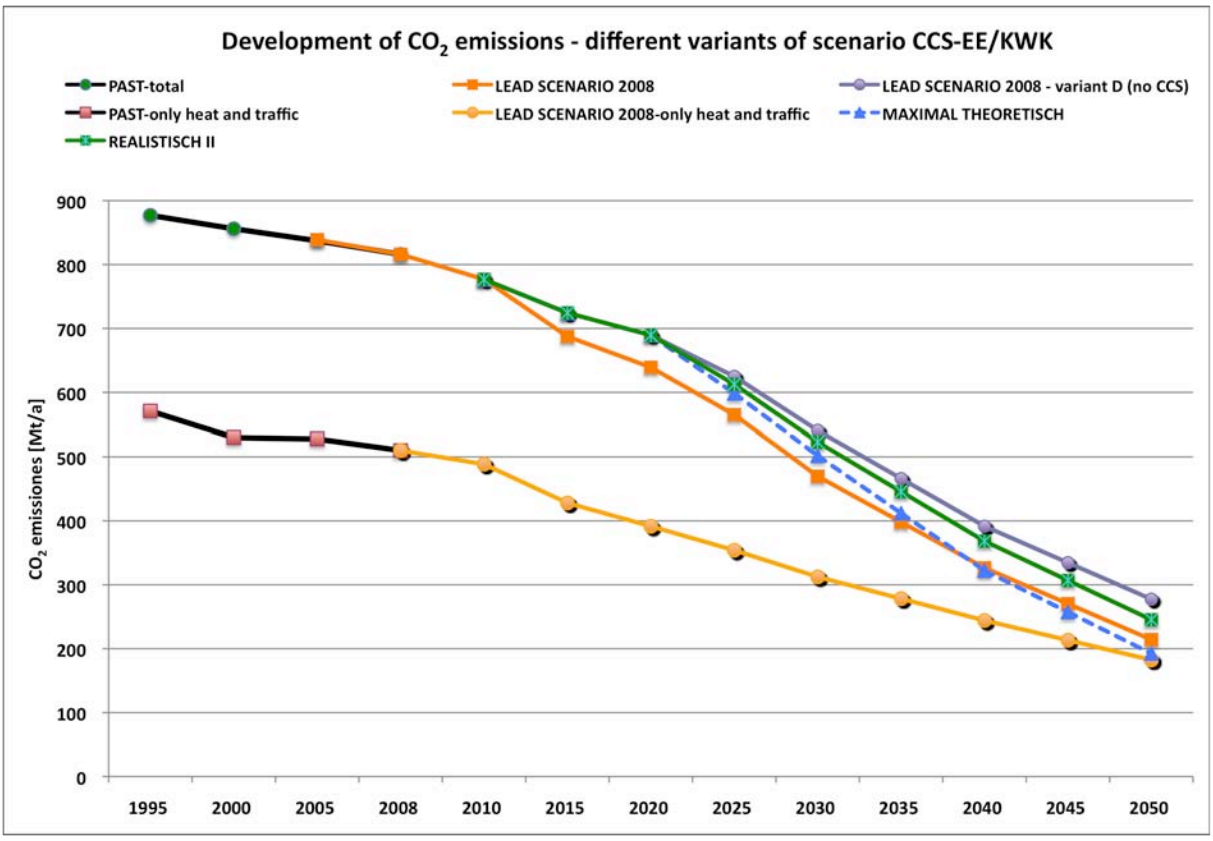

Fig. 10-2 Range of the development of total CO_2 emissions, subdivided into the electricity sector and the sectors of consumption “heat + fuels” for two variants of scenario CCS-EE/KWK and comparison with the Lead Scenario 2008

Source: Authors’ design

A comparison of CO_2 emissions in the different variants of the CCS-EE/KWK scenario in the electricity sector alone is given in Fig. 10-3. First of all, it becomes apparent that the CO_2 reduction potential of the expansion of renewables in scenario D is considerably larger that than of a potential reduction through CCS power plants (curve "renewables frozen"). This is the result of the assumed considerable expansion of renewable energies in this scenario, which generally reduces the share of electricity generated by fossil fuels by a considerable extent.

In this scenario, however, the considerably higher CO_2 emission from electricity generation occurring up to 2020 will be significantly reduced compared to the Lead Scenario 2008, depending on the intensity of the expansion of CCS up to 2050. In case 2 (Maximal – Realistisch), the state of the Lead Scenario is virtually reached, at approximately 28 million tonnes of CO_2 per annum. In the more realistic variants 4 (Realistisch I) and 6 (Realistisch II), levels of 50 and 63 million tonnes of CO_2 per annum, respectively, are achieved. The level of the Lead Scenario (28 million tonnes of CO_2 per annum) is hence exceeded by 22 million tonnes of CO_2 per annum (variant 4, plus 80 per cent) and 35 million tonnes of CO_2 per annum (variant 6, plus 125 per cent), respectively.

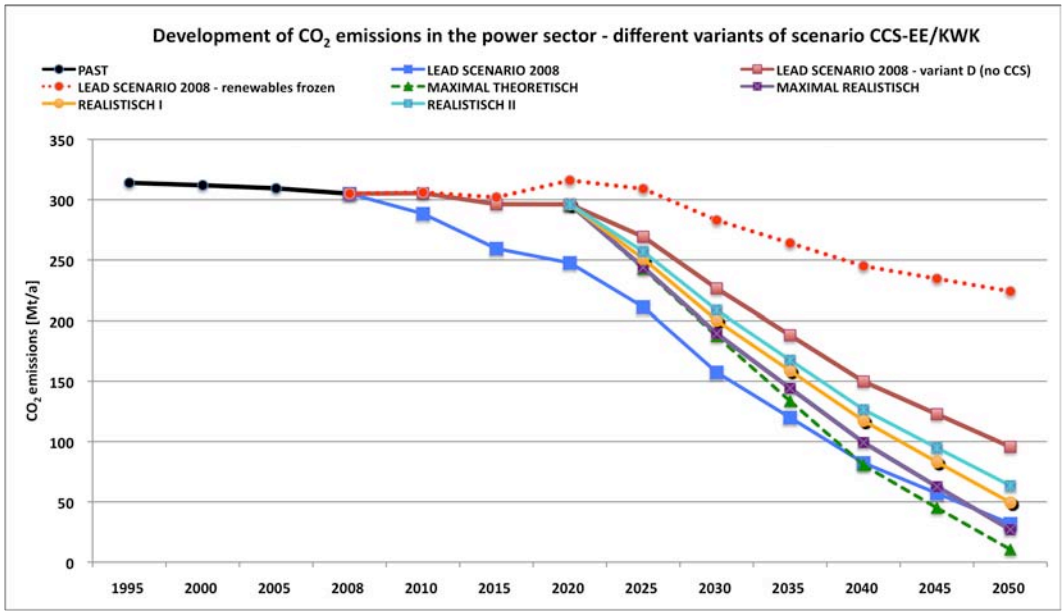

Fig. 10-3 Course of CO_2 emissions in the electricity sector in the different variants of scenario CCS-EE/KWK, in the Lead Scenario 2008 and in the hypothetical case of freezing the contribution of renewables at today's level

Source: Authors' design

The complete comparison of the most important key data of the variant calculation according to Tab. 10-3 is shown in Tab. 10-4 (a detailed overview of the key data of the six scenarios can be found in Tab. 13-4 to 13-9 in the Appendix). The following are presented in addition to the avoided CO_2 – compared to the CO_2 emissions of the standard operation of fossil fuel-fired power plants: the "net capacity" of the power plants accessible for CCS measures; the quantity of electricity that can be produced; the resulting capacity of the CCS power plants, including the additionally required power to compensate for the reduced efficiency of power plants due to the capture of CO_2; the total quantity of CO_2 to be captured and the additional need for fuel.

Tab. 10-4 The effects of using CCS technology in the new construction and retrofitting of fossil fuel-fired power plants for various framework conditions

		Unit	2025	2030	2040	2050
1. Maximal – Theoretisch CCS for 100% new STP and new CHPP; Retrofitting also at 100%	**CCS – capacity *)**	**GW_{el}**	**10.9**	**17.3**	**37.7**	**50.1**
	Net capacity	GW_{el}	8.8	14.0	30.9	40.8
	Net electricity generation	TWh/a	42.9	64.0	121.9	146.4
	Avoided CO_2 *)	Million t/a	26.5	39.1	69.3	85.1
	CO_2 to be captured *)	Million t/a	36.7	54.1	94.5	116.5
	Additional demand for fuel	PJ/a	80	118	206	254
2. Maximal – Realistisch CCS for 100% new STP and 75% new CHPP; Retrofitting for 65% STP and 35% CHPP	**CCS – capacity *)**	**GW_{el}**	**9.9**	**15.4**	**26.3**	**37.7**
	Net capacity	GW_{el}	8.0	12.4	21.5	30.6
	Net electricity generation	TWh/a	40.7	59.7	88.1	116.0
	Avoided CO_2 *)	Million t/a	25.4	36.9	50.6	68.6
	CO_2 to be captured *)	Million t/a	35.2	51.2	69.0	94.6
	Additional demand for fuel	PJ/a	77	112	150	208
3. Maximal – Neu CCS for 100% new STP and 75% new CHPP; *no* retrofitting	**CCS – capacity *)**	**GW_{el}**	**9.9**	**15.4**	**19.7**	**29.6**
	Net capacity	GW_{el}	8.0	12.4	16.0	23.8
	Net electricity generation	TWh/a	40.7	59.7	67.5	91.0
	Avoided CO_2 *)	Million t/a	25.4	36.9	40.1	54.4
	CO_2 to be captured *)	Million t/a	35.2	51.2	55.4	75.8
	Additional demand for fuel	PJ/a	77	112	122	171
4. Realistisch I CCS for 75% new STP and 40% new CHPP; Retrofitting for 40% STP and 20% CHPP	**CCS – capacity *)**	**GW_{el}**	**6.8**	**10.3**	**16.2**	**24.2**
	Net capacity	GW_{el}	5.5	8.3	13.2	19.6
	Net electricity generation	TWh/a	29.0	41.9	56.0	77.0
	Avoided CO_2 *)	Million t/a	18.3	26.2	32.5	46.1
	CO_2 to be captured *)	Million t/a	25.4	36.5	44.5	63.8
	Additional demand for fuel	PJ/a	56	80	97	141
5. Realistisch I – only KOHLE as in variant 4, but without gas power plants	**CCS – capacity *)**	**GW_{el}**	**6.5**	**9.6**	**13.4**	**20.3**
	Net capacity	GW_{el}	5.2	7.7	10.8	16.3
	Net electricity generation	TWh/a	28.1	40.1	48.9	68.6
	Avoided CO_2 *)	Million t/a	18.0	25.7	30.5	43.7
	CO_2 to be captured *)	Million t/a	25.1	35.8	41.9	60.8
	Additional demand for fuel	PJ/a	55	78	89	132
6. Realistisch II CCS for 50% new STP and 30% new CHPP; Retrofitting for 30% STP and 15% CHPP	**CCS – capacity *)**	**GW_{el}**	**4.7**	**7.1**	**11.7**	**17.2**
	Net capacity	GW_{el}	3.8	5.7	9.6	13.9
	Net electricity generation	TWh/a	19.7	28.5	40.2	53.9
	Avoided CO_2 *)	Million t/a	12.3	17.8	23.3	32.1
	CO_2 to be captured *)	Million t/a	17.2	24.7	31.6	44.4
	Additional demand for fuel	PJ/a	38	54	69	98
*) taking into consideration the additional required capacity and higher emissions due to the reduction of efficiency in CO_2 capture ("penalty load"), compared to the reference power plant without CCS						

Source: Authors' design

The potential scope of capacity provided by CCS power plants in 2050 ranges from a total of 17 GW capacity in the “Realistisch II” case (6) to the realistic upper limit “Maximal – Realistisch” of almost 38 GW capacity (2). The (rather more unrealistic) case “Maximal – Theoretisch” yields a capacity of 50 GW (1).

Due to efficiency losses in CCS power plants, the quantity of CO_2 *to be captured* (Fig. 10-4) is considerably larger than the quantity of CO_2 *avoided* without CO_2 capture, compared to the respective reference power plants. In the comparison of the realistic variants, the quantity of CO_2 occurring in 2050 ranges from 44 million tonnes of CO_2 per annum in the “Realistisch II” case to 95 million tonnes of CO_2 per annum in the “Maximal – Realistisch” case. In the period from 2020 to 2050, a cumulated quantity of 832 and 1,769 million tonnes of CO_2 per annum, respectively, is yielded in these two variants.

If the capacity of CCS power plants remains constant after 2050, additional amounts of 445 and 950 million tonnes of CO_2 occur, which will need to be kept in suitable storage facilities (see also Section 10.7).

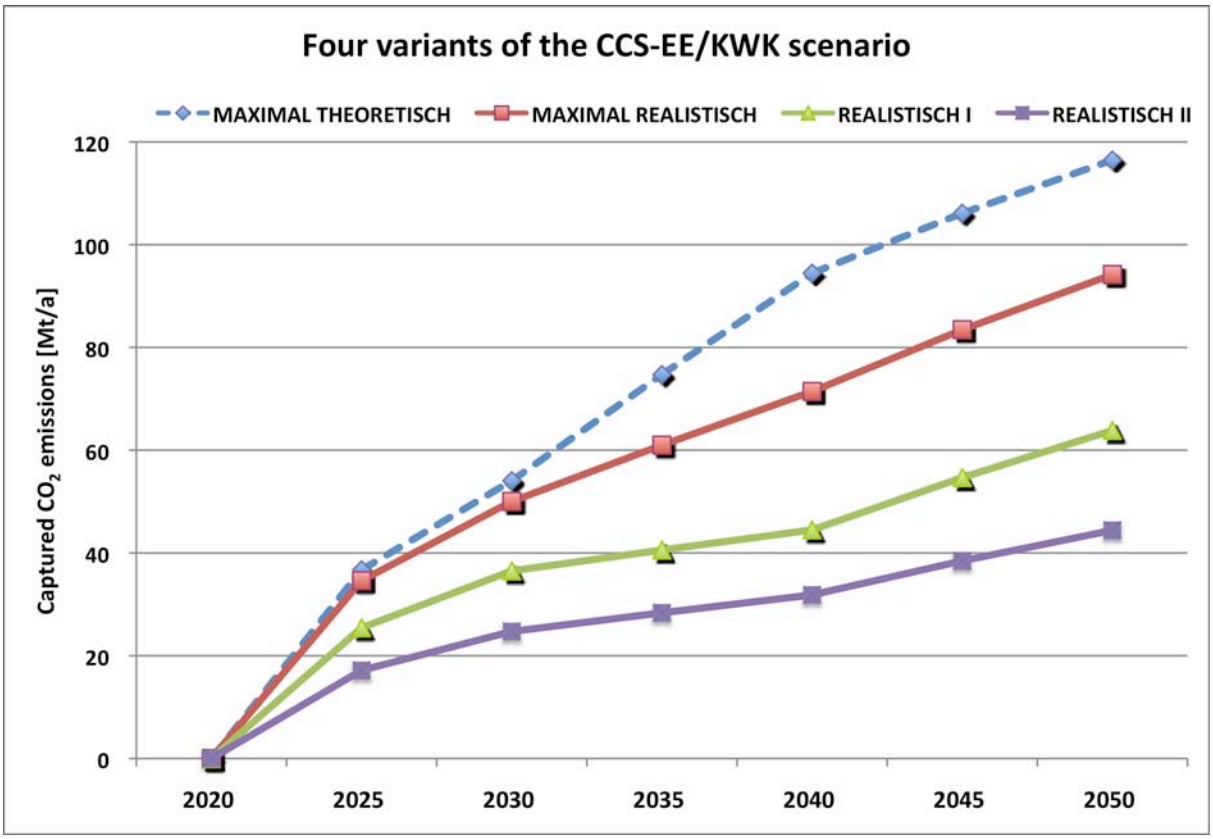

Fig. 10-4 Annual quantities of CO_2 to be captured and stored in four variants of scenario CCS-EE/KWK

Source: Authors’ design

The additional consumption of fossil energy resulting from the efficiency loss is a further characteristic of CCS electricity generation. In 2050, it amounts to between 2.1 and 4.4 per cent of the total energy-related use of primary fossil fuels for this year – again within the range of the above two cases “Realistisch II” and “Maximal – Realistisch”. Related to the use of fuel for electricity generation (condensation power stations and CHP), it ranges from 5.4 to 11.3 per cent.

Fig. 10-5 and Fig. 10-6 show the relationship between CCS electricity generation and CCS capacity, compared with the overall system of power supply in the event of the implementation of scenario variant D. The constant expansion of renewable energies dominates the electricity supply. The desired expansion of CHP in the decentralised area further restricts the scope for the use of CCS technology. Even in the relatively optimistic case "Realistisch I", electricity generation from CCS power plants therefore only makes up a 12 per cent share of the total power generation in 2050. The achievable proportion of capacity is lower, at 10.6 per cent.

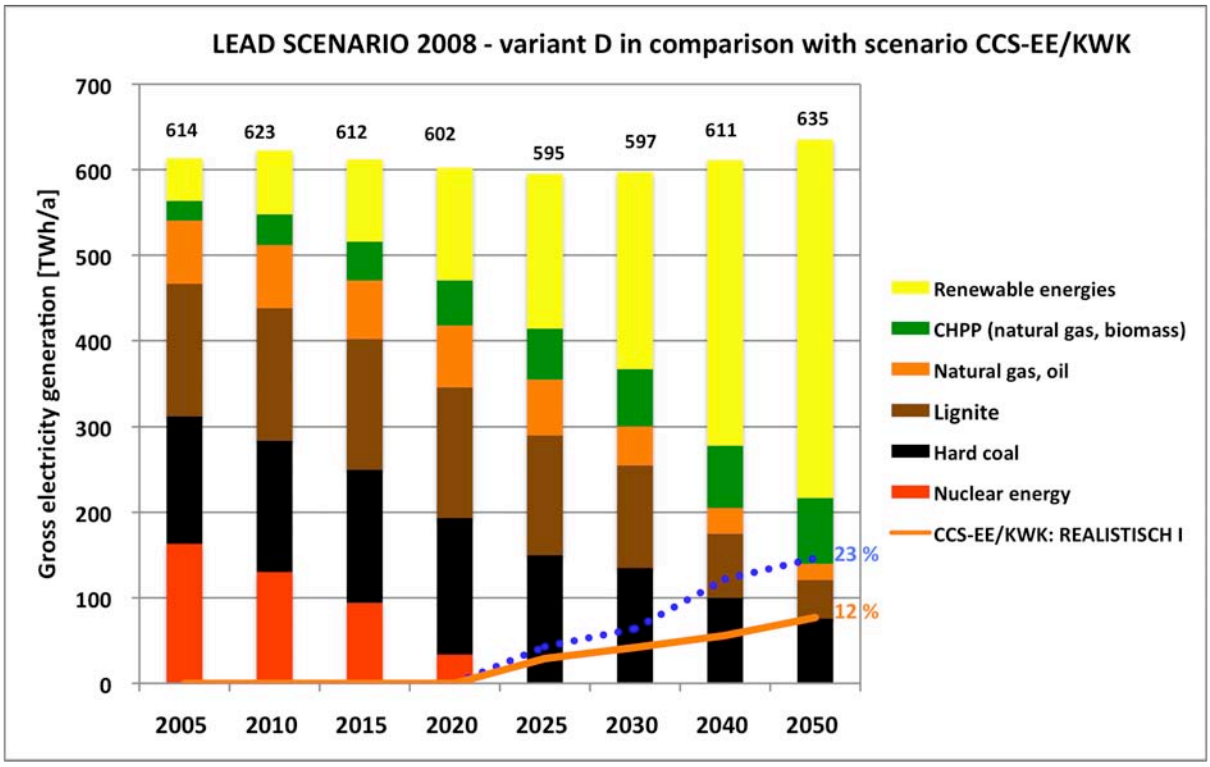

Fig. 10-5 Overall electricity generation in variant D of the Lead Scenario 2008 and contribution of CCS in two variants of scenario CCS-EE/KWK

Source: Authors' design

It must also be taken into consideration that an assumption has been made, in favour of CCS, that all "new power plants" fired by fossil fuels (maximum 8 GW) constructed between 2005 and 2010 will also be replaced by CCS plants by 2050, after their 40-year service life. These CCS power plants would remain on the grid up to the period of 2085 to 2090, which of course would have an impact on the further expansion of electricity generation from renewables from 2050.

Fig. 10-7 shows the CCS capacity to be installed according to power plant types in the "Realistisch I" case. On average, 1 GW CCS capacity must be installed annually between 2020 and 2030; the value drops to an average of 0.55 GW/a between 2030 and 2050. Of the 24 GW CCS power plants installed in 2050, 13 GW are from hard coal-fired power plants, 7 GW from lignite-fired power plants and 4 GW from natural gas power plants. Compared with the "Maximal – Theoretisch" case, it can be seen that almost 50 per cent of all large-scale power plants fired by fossil fuel existing in 2050 will be equipped with CCS in the "Realistisch I" case.

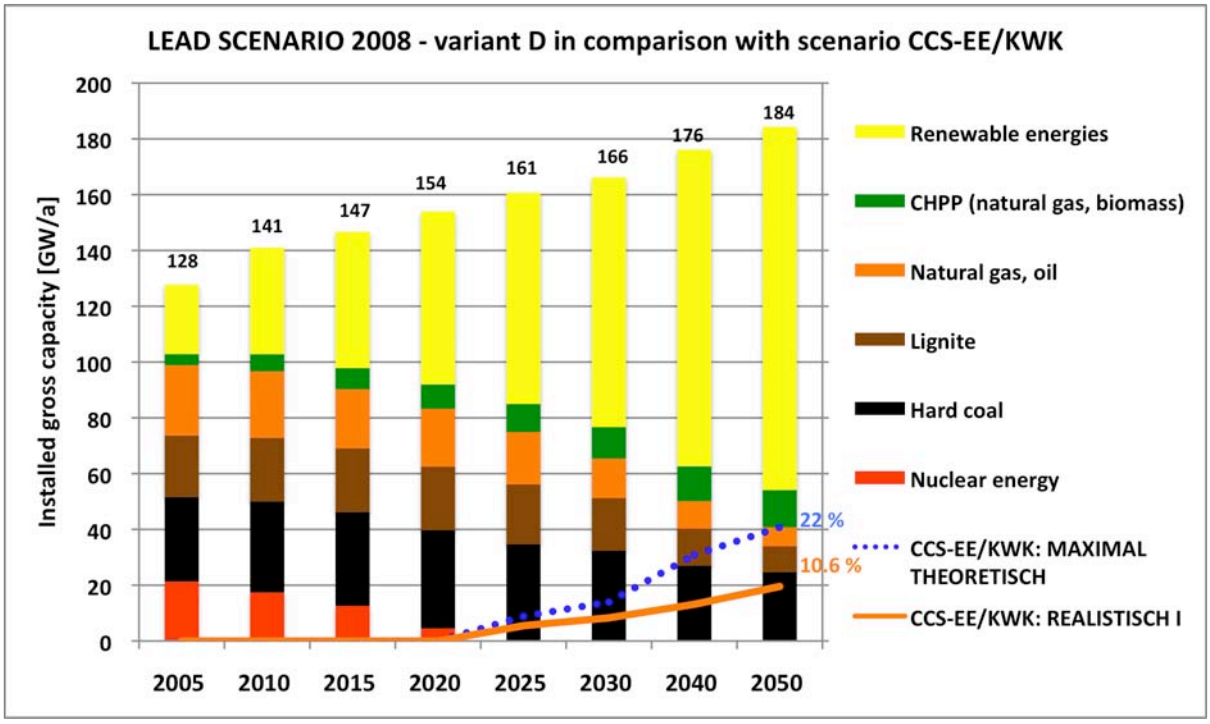

Fig. 10-6 Development of the power plant capacity in variant D of the Lead Scenario 2008 and contribution of CCS in two variants of scenario CCS-EE/KWK (without "penalty load" of CCS power plants)

Source: Authors' design

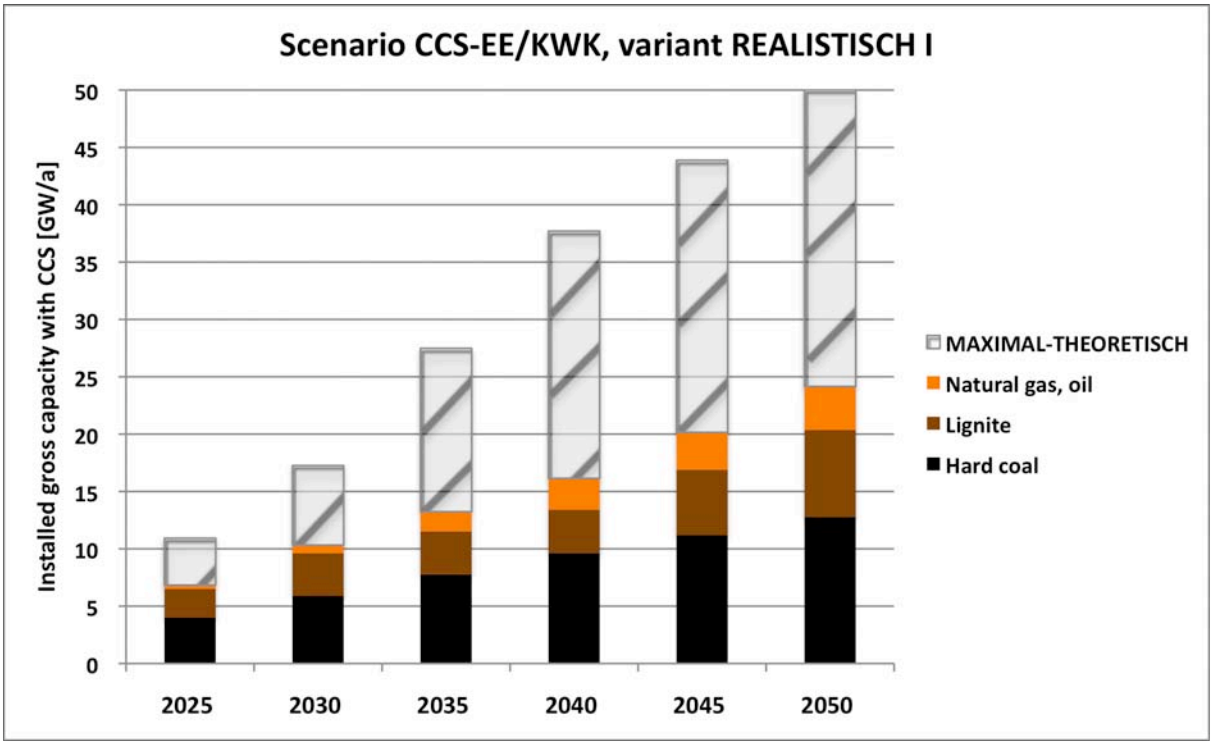

Fig. 10-7 Capacity of CCS power plants according to energy sources in scenario CCS-EE/KWK (variant 4: Realistisch I) and theoretical upper limit (variant 1: Maximal-Theoretisch)

Source: Authors' design

10.6 Conclusions from the scenario analysis

The potential role of CCS in the context of a German climate protection strategy largely depends on previously selected energy strategies. In the occurrence of a continued significant expansion of renewables and a steadily increasing share of combined heat and power generation in the German power supply, as shown in variant D of the Lead Scenario 2008, the scope for a further reduction of CO_2 in the remaining fossil segment of power supply using CCS is considerably restricted. In the ideal case, variant "Realistisch I", with an installed CCS capacity of 24 GW, an average of 46 million tonnes of CO_2 could be saved annually up to 2050, compared with an equally sized electricity generation without CCS. This amount constitutes 18 per cent of the total avoidable CO_2 emissions in the electricity sector between 2005 und 2050, and 8 per cent of that within the entire power supply.

The CO_2 reductions achieved by expanding renewable energies and increasing efficiency in the supply of heat and fuel are considerably larger for the same period. Even if there is a great deal of uncertainty surrounding the costs involved, there is much to suggest that an energy path characterised more strongly by renewable energies would be cheaper in the medium to long term. However, it would necessitate a considerable restructuring of the power industry and infrastructure – including the need for not only completely different network structures but also energy storage facilities. In any case, CO_2 reductions created by efficiency improvements in the electricity sector can be achieved economically with high returns.

The Lead Scenario 2008 and scenario variant D are based on the assumption of a scheduled phasing out of nuclear energy. This leads to the creation of a demand for power plant capacity to fill this gap. This could then be met by renewable energies and carbon capture technologies. However, energy policy-makers are discussing the possible extension of the operational life of nuclear power plants. If this were to happen, the opportunity for implementing CCS is significantly reduced. This would impact upon the objective to realise a considerable expansion in the share of renewable energies in electricity generation.

Consequently, there may only be a "suboptimal" contribution left for potential CCS power plants if it is assumed that considerable financial resources will be required for further research, development and demonstration before CCS is commercially available. If, moreover, the earliest opportunity for deployment remains around 2020, it is vital to enable the new fossil fuel-fired power plants to be retrofitted as far as possible – even for medium-sized combined heat and power plants – otherwise the achievable segment would be reduced even further.[76] In addition, a completely different mix of renewable energies, compatible with an appropriate CCS power plant fleet, would be necessary, a mix that is not suitable for compensating for fluctuating energies.

It follows from the analysis that the existing energy policy objectives of considerable improvements in efficiency (a doubling of energy productivity by 2020 compared to 1990 levels; a 25 per cent share of combined heat and power generation in 2020) and the required sig-

76 However, it would be conceivable to postpone the coal-fired power plants currently at the planning stage and to initially concentrate on the planned expansion of renewable energies (50% share of power generation in 2030). If CCS power plants were commercially available on a suitable scale in 2030, no power plants would have to be retrofitted, but could be directly built from scratch.

nificant expansion of renewable energies (a 30 to 35 per cent share of renewable energies in electricity generation by 2020 and an approximately 50 per cent share by 2030) leave only minimal scope for the substantial use of CCS technology, even in the case of ambitious climate protection targets. On the other hand, use of CCS technology would be prudent in a future energy supply that only achieves moderate successes in increasing efficiency and further expanding renewable energies, and which shows only little change compared to the current situation with regard to its structural features.

10.7 Infrastructure expenditure for the transport and storage of the captured carbon dioxide

Requirements concerning infrastructure planning

Finally, we will take a look at the infrastructure required to transport and store the captured CO_2. For this purpose, the scenarios considered in the RECCS study and the aforementioned scenario family CCS-EE/KWK, with its six sub-variants, will be explored. It is essential to analyse the issue of infrastructure because, in practice, three challenges must be met simultaneously at the time of the CCS injection, as considered in the scenarios:

- It must be ensured that capture plants can be installed on a large scale within short periods of time.
- Suitable storage facilities must be available for the planned quantities of captured carbon dioxide. To this end, each individual storage formation must first be examined to ascertain its suitability. Then injection devices must be installed. Once storage has commenced, a monitoring programme is set up to establish, over the period of around five years, whether the storage is indeed suitable for depositing CO_2.
- By the time the individual power plants are ready for operation, a transport system (presumably pipelines) must also be in place. Since the volumes of storage formations are generally restricted, and 600 million tonnes of CO_2 can be captured from a power plant the size of Neurath (2,200 MW_{el}) alone throughout its life, one single pipeline to a storage facility will not suffice – a network of pipelines with a number of basins will be necessary.

It must be considered for all three aspects that appropriate capacities must be planned and constructed not only in Germany, but presumably also in the Netherlands, Poland, England, Spain and Denmark.

Overview of the quantities of captured carbon dioxide in the scenarios

In order to enable an assessment of the impact on a CO_2 infrastructure to be made, Tab. 10-5 shows the annually occurring quantities of captured CO_2 for the RECCS scenarios “CCS-MAX” and “CCS-BRIDGE” and the aforementioned scenario family CCS-EE/KWK, with its six sub-variants. For information only, the results of a study commissioned by the Federal State of North Rhine-Westphalia is also presented. In this study, the impact of a “CCS-Max strategy” for NRW was analysed (WI 2009). In addition, the cumulated quantities of CO_2 up to 2050 are given in the right-hand column.

While the annual quantities of captured CO_2 from all power plants determine the *capacity of the pipeline(s)* (and hence their diameter and width), the quantities calculated over the entire

life of the power plants show how much *total storage capacity* has to be maintained for these power plants.

The greatest range, from 6.2 to around 9.7 billion tonnes, occurs in the RECCS study scenarios. Due to the other assumptions in our study and the low requirement for the use of CCS, the variants of the scenario family CCS-EE/KWK only require a total storage capacity of between 0.8 and 2.2 billion tonnes, or between 0.8 and 1.8 billion tonnes if we only look at the realistic variants. If only NRW is considered, up to 4.8 Gt occur there alone in a strategy comparable to CCS-MAX.

Tab. 10-5 Quantities of captured carbon dioxide in the variants of the new scenario CCS-EE/KWK and the RECCS scenarios CCS-MAX and CCS-BRIDGE

	2025	**2030**	**2040**	**2050**	**2020-2050 Cumulated**
	Million t/a	**Million t/a**	**Million t/a**	**Million t/a**	**Million t**
RECCS – CCS-MAX *)	94	242		586	9,648
RECCS – CCS-BRIDGE *)	85	187		328	6,207
RECCS – NaturschutzPlus	0	0		0	0
Scenario family CCS-EE/KWK					
1. Maximal – Theoretisch	36.7	54.1	94.5	116.5	2,153
2. Maximal – Realistisch	35.2	51.2	69.0	94.6	1,764
3. Maximal – Neu	35.2	51.2	55.4	75.8	1,361
4. Realistisch I	25.4	36.5	44.5	63.8	1,192
5. Realistisch I – only Kohle	25.1	35.8	41.9	60.8	1,155
6. Realistisch II	17.2	24.7	31.6	44.4	830
For information only, **NRW CCS Study 2009** (WI 2009) (maximum use of CCS in NRW from 2020 for power plants and other point sources)				33–131 (only NRW)	1,172–4,754 (only NRW)
For comparison (see Section 7.5): **Storage potential of Germany** according to the WI estimate according to GeoCapacity according to BGR					5.000 (4.000 / 15.000) 17,000 19,000–41,000
*) Including separated CO_2 from coal gasification in the production of hydrogen for the transport sector					

Source: Authors' design

Comparison of captured carbon dioxide and storage capacities

If the generated quantities of captured CO_2 are compared with the storage capacities for Germany derived in this study, the emissions occurring in the scenario family CCS-EE/KW up to 2050 would also be able to be stored within Germany in the cautious, conservative case (storage potential of 5 billion tonnes of CO_2). If both sensitivity analyses are considered, in the higher variant (storage potential of 15 billion tonnes of CO_2) the CO_2 quantities from the other scenarios could also be stored in Germany. If the CCS power plants also remained on

the grid beyond 2050, between 445 and 950 million tonnes of CO_2 would be added to this amount every decade.

In general, this contemplation assumes that the estimated capacity is indeed utilisable, that CSS is accepted and that a suitable transport infrastructure can be installed. The latter aspect will now be explored in the following section.

Construction of a transport infrastructure

Due to time constraints, it is not possible for us to develop our own infrastructure plan in this study; in place of this, we take the results of the study for the Federal State of North Rhine-Westphalia for comparative purposes. In the NRW study, the analysed power plants (and other large point sources) were divided into six clusters. The aim was to include as many large CO_2 emitters as possible within a compact area, which acted as focal points for the successive construction of a CO_2 infrastructure (WI 2009).

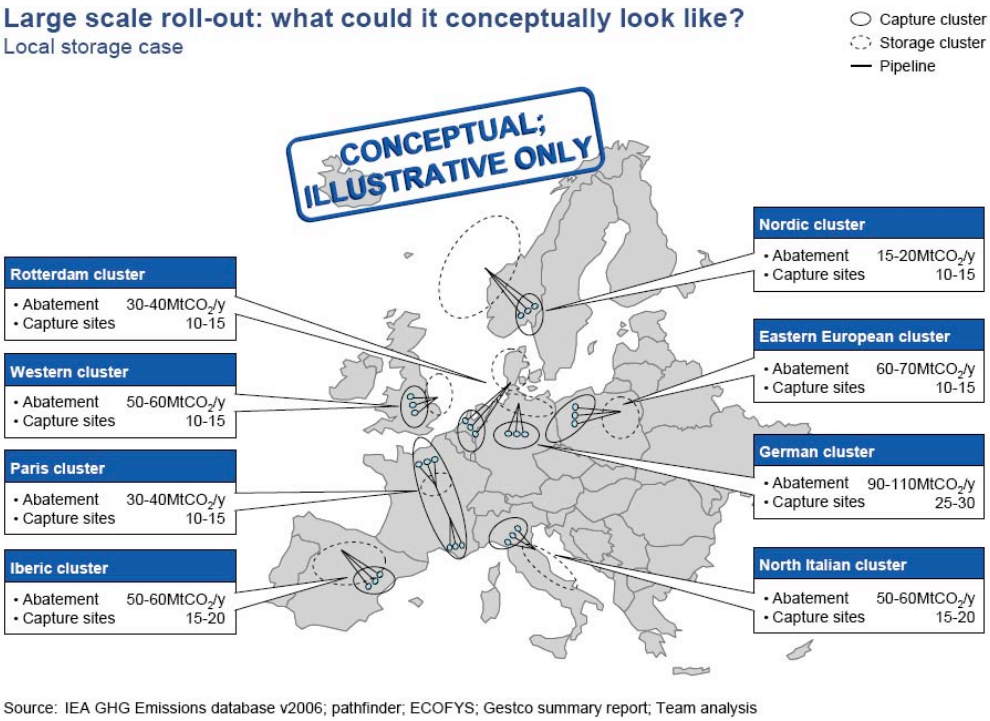

Fig. 10-8 Draft of a Europe-wide cluster of CO_2 sources

Source: McKinsey 2008

Proposals have been made to create clusters throughout Europe based on the Ruhr model. In a concept by McKinsey (Fig. 10-8), NRW is the central cluster of a European grouping, comprising eight clusters. (McKinsey 2008:34) states three advantages of creating such clusters:

- It is less expensive to transport CO_2 in a few large pipelines than in lots of small ones. As an example, use of one 36-inch pipeline in place of two single 24-inch pipelines would reduce transport costs by 30 per cent;
- In regions where no problems exist regarding the acceptance of CCS, as many emitters as possible should be connected to an extensive network;

- Most of the largest emitters are situated in highly industrialised regions. In this case, a CCS cluster could also serve as a focal point for the advancement or diversification of existing industry.

The transport routes portrayed in Fig. 13-1 (see Appendix) give an example of transport expenditure if the quantities of CO_2 captured in the maximum case for NRW, 131 million tonnes of CO_2 per annum, would have to be transported. They are in the same range as the maximum quantities of 117 million tonnes of CO_2 per annum generated for the Maximal – Theoretisch variant.

Three cases can be differentiated here:

a) Onshore storage in (randomly selected) formations in northern Germany (total pipeline length 4,330 km)

b) Offshore storage in the Utsira formation near Norway (8,380 km)

c) Transfer to the planned Dutch CO_2 network and transit to Dutch offshore formations (1,140 km, German section only).

Depending on the density of the routes, generated using a geographic information system and highlighted in different colours, up to ten parallel pipelines are required. If the “Maximal-Theoretisch” variant were implemented, a transport expenditure of the same high magnitude would be expected. It goes without saying that other power plant sites would have to be taken into consideration – this presentation merely highlights the infrastructural requirements for such a CCS strategy.

11 Conclusive integrated assessment of CCS for fossil fuel-fired power plants and research recommendations

11.1 Objectives

The development and demonstration of CCS for fossil fuel-fired power plants has become increasingly prominent in Germany, the rest of the European Union and many other countries (China, the USA and Australia were analysed).

Particularly at the *international level*, CCS is considered to be vital for meeting global targets for reducing CO_2. In its "Blue Map" scenario of "Energy Technology Perspectives", for example, the International Energy Agency estimates that a 50 per cent reduction in global CO_2 emissions by 2050 (compared to current levels) would require a 48 gigatonne reduction in CO_2 compared to the business-as-usual path (IEA 2008). It has been calculated that CCS can make a 19 per cent contribution to this decrease, with the CO_2 being captured from power stations and industrial sites in roughly equal measures. The maximum reduction in CO_2 as a result of using CCS is 9.1 gigatonnes. Consequently, CCS would make a substantial contribution to achieving the 50 per cent reduction target.[77]

The *European Union* also supports the development and take-up of CCS technology. One of the aims, triggered also by deliberations about improving the security of supply, is to be able to use the resource potential of coal without multiplying greenhouse gas emissions. Nevertheless, the European Commission has stated that it believes CCS to be "highly important" from a global perspective. This is because coal reserves will have to be used in future, not only to supply energy to Europe, but also to meet the ever-increasing need for energy in developing and transition countries (European Commission 2008). In the SET Plan ("European Strategic Energy Technology Plan"), adopted in 2007, CCS is listed as one of six key technologies to be supported in terms of industrial policy up to 2020. To work towards achieving this target, the EU has devised a "CCS Directive" within the space of just one year. This directive came into force in June 2009 as part of the "Green Package" (see Sections 2.1.2 and 6.1).

Although no quantitative targets have yet been set in *Germany*, a variety of development projects have been funded by the German Federal Ministries of Economics and Technology (BMWi) and Education and Research (BMBF). The further development of the climate-friendly generation of electricity from coal is identified as an important task in the integrated energy and climate protection programme. With a few exceptions, political parties, trade unions and industry associations are in favour of further testing and gradually implementing CCS technology. The "energy concept", which is expected to be passed by the German government in autumn 2010, is likely to provide at least a basic statement on the potential share of CCS in German reduction targets.

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[77] According to findings from climate research, a 50 per cent reduction target will not suffice to limit the rise in temperature to 2 degrees. In fact, the IPCC assumes that a minus 50 to minus 85 per cent global reduction in greenhouse gas emissions in 2050 compared to 2000 is quite likely to be required to restrict the temperature limit (IPCC 2007).

Numerous capture processes are being developed worldwide using the various available individual technological options. The majority of the research projects are concentrating on the post-combustion process, for which there are also the most suppliers. In addition to a variety of capture processes within the absorption, adsorption and membrane methods, recent interest has focused on biological processes (using algae or enzymes). Despite the fact that post-combustion technology is the least efficient of these processes, research into this technology has been prioritised with a view to potentially retrofitting power stations.

11.2 Factors determining the introduction of CCS

If we focus on the state of the technical development, policy frameworks and previously published scientific research, six crucial factors determining the introduction of CCS should be highlighted. It is vitally important to consider CCS as part of an over-arching analysis of several climate protection options, rather than from an individual perspective.

1. Large-scale availability of the technology

Numerous uncertainties exist with regard to the applicability of CCS and the resulting (quantitative) role of CCS for climate protection. One of these main uncertainties is the issue of how much time will elapse between the end of testing and actual commercial realisation.

Previous experience has shown that upgrading from pilot plant stage to large-scale commercial availability (here 700 to 2,000 MW_{el} power plant capacity) cannot usually be achieved in anything less than ten years. This difficulty is compounded by the fact that there is considerable need for further research and development before CO_2 separation can be deployed. Moreover, in the case of CCS, it is not simply “just” about the actual power plant and CO_2 capture. The other links in the CCS chain must also be ready for operation at the same time: a CO_2 transport infrastructure must be established; operational and safe storage sites must be available, which must be able to absorb the enormous quantities of CO_2 emitted from a large-scale power plant (100 to 400 million tonnes for the duration of its lifespan) from the moment they occur. Taking just one aspect of the process, the European Technology Platform estimates that it will probably take up to 6.5 years for a storage site to be approved; it expects the whole chain of one single CCS project to be realised in 6.5 to 10 years (ZEP 2008:23).

For this reason, commitment to the timescale for commercial availability of the whole CCS chain (separation, transport and storage) is consistently being deferred in the latest publications and announcements by industry. The years between 2025 and 2030 are now increasingly being referred to as the time by which the technology will be ready for operation (MIT 2007, ZEP 2008, Greenpeace 2008). The uncertainties regarding the availability of the technology are reflected in individual companies’ business activities. Dong Energy, for instance, announced that it intends to follow a different course beyond fossil fuels in the medium term in Germany. Other companies believe the commercialisation phase of CCS will not begin until 2030 at the earliest.

From the perspectives of the power industry and climate policy, the implications of a later implementation of CCS should be reviewed in the context of the call by climate scientists that global CO_2 emissions must peak sometime between 2010 and 2020 to trigger a reduction towards a 450 ppm path in time (IPCC 2007). For this reason, the agenda for global climate

protection must be set in the next ten years. Essentially, this can only succeed using technologies that are established and basically applicable now.

These include the whole range of technologies to increase energy efficiency and, primarily, renewables. To this end, the European Union has already adjudicated that its Member States feed 20 per cent of their total energy requirements from renewable energies by 2020; the figure is expected to increase steadily after this date. In Germany, this signifies a commitment to cover 18 per cent of final energy consumption and, following exemplary calculations to this end, at least 30 per cent of power consumption from renewable energies by 2020. This figure is by no means overambitious if renewable energies continue to expand any way near as dynamically as they have done over the last 15 years. Even if considerable effort is still required to achieve these targets with regard to establishing a suitable infrastructure (expansion of power networks, power storage), this potential outcome nevertheless leads to conclusions that:

- the use of CCS for power plants (assuming the later availability of the technology) increasingly loses the potential role ascribed to it as a bridging technology;
- CCS for power stations could primarily play a supplementary role (for example, if the further expansion of renewable energies should stagnate, or the full potential of energy efficiency be exhausted) or
- the implementation of CCS technology will increasingly focus on other large point sources from the industrial sector, where the fields of application of renewables and other climate protection measures are limited.

2. Available potential for CCS

The potential role of CCS depends not only on the expected timing of its application but also on general developments in the fossil fuel-fired power plant sector. Due to the current power plant regeneration programme, CO_2 capture has arrived too late to be included directly in the planning phase of the majority of fossil fuel-fired power installations in Germany. For this reason, the issue of retrofitting power plants is of major importance for the implementation of CCS technology in Germany. Various economic criteria are involved here, including an adequate remaining service life or, expressed differently, an adequate maximum age of the plants, as a prerequisite. In McKinsey's analyses, for instance, a lifespan of 12 years is assumed, after which it is not worth retrofitting a power plant with CO_2 capture facilities (McKinsey 2008).

It is crucial, therefore, that power stations currently under construction can be retrofitted at a later stage. Capture readiness is mandatory for new power plants according to the CCS Directive of the European Union. Tests must prove that suitable storage sites are available, that transport facilities are technically and economically feasible and that CO_2 capture installations can be retrofitted. The draft of the German CCS law (and subsequently the amendment of the 13th Federal Immission Control Ordinance), however, only specified that suitable space must be set aside at the site. Permits granted would then also be considered valid if no suitable CO_2 storage sites were available, or if there was technical and economical reasonable access to CO_2 pipelines, or if it was not technically possible or economically reasonable to retrofit CO_2 capture plants.

In spite of the current wisdom about the maximum age for retrofitting power stations, in the scenario analysis presented here, an optimistic outlook is presented, assuming that the retrofit could be carried out even 20 years after the construction of the plant. Furthermore, it assumes that CCS will be available from 2020. In the best outcome, (scenario "Realistisch I"), an average of 46 million tonnes of CO_2 can be avoided annually up to 2050 with an installed CCS capacity of 24 gigawatts (new construction of 75 per cent of steam and 40 per cent of combined heat and power stations with CCS; retrofitting of 40 per cent of steam and 20 cent of combined heat and power plants), totalling 1.2 billion tonnes by 2050. This amount constitutes 18 per cent of the total avoidable CO_2 emissions in the electricity sector between 2005 and 2050, and 8 per cent of that within the entire power supply system. It is assumed here that, by complying with existing basic political goals, not only the above-mentioned targets to expand the share of renewable energies, but also the doubling of energy productivity by 2020 (compared to 1990 levels) and the share of combined heat and power, rising to 25 per cent, will be detrimental to exploiting the full potential of CCS. The analysis therefore shows that

- even with ambitious climate protection targets, there is little room for a substantial use of CCS technology (in power plants) in Germany if the stipulation of expanding CHP and increasing energy productivity is to be adhered to simultaneously;
- this potential is reduced considerably further if the commercial implementation of CCS is postponed to 2025 or 2030 (whilst retaining the intention to achieve a dramatic rise in the share of renewable energies by 2050[78]);
- an extension of the operating lives of nuclear power plants is currently under discussion, which would significantly reduce the potential for introducing CCS (in power plants) in Germany.

3. Development of the relative costs of power plants with CCS and renewable energies

The economic assessment of power plants with downstream CCS depends not only on the question of when the additional costs for CO_2 capture are lower than the costs for acquiring CO_2 allowances. It is more about determining relative cost effectiveness. To this end, the timing of competing climate protection options, such as renewables, must also be taken into account. The analysis carried out in the present study principally confirms the findings of the first RECCS study. Although the costs of fossil fuel-fired power plants and renewable energies are higher than in the previous study, the break-even point at which the electricity generating costs of renewables will be cheaper than those of CCS power plants will still fall between 2020 and 2030. If the dynamics of the expansion of renewables in the electricity sector remain high, individual renewable energy technologies (offshore and onshore wind power, solar thermal power plants) will be able to compete with CCS power plants as early as in 2020. An average mix of renewable energies assumed here is showing signs of being partially competitive already.

[78] According to a statement by the German Minister of the Environment Dr. Röttgen, the new German government has "stated the objective to almost entirely convert power generation to renewable sources by 2050" (BMU 2009b).

- If fuel prices increase *considerably* and the cost of CO_2 permits remains low, the generating costs of CCS-based natural gas and hard coal-fired power plants will be higher than with renewable energies from 2020. Lignite-fired CCS power plants will follow from 2025 (offshore wind/solar thermal energy) and 2030 (mix of renewable energies).
- Even in the case of *very low* increases in energy prices (but higher CO_2 penalties), the additional costs incurred by CCS would be so high that renewable energies would remain competitive at the same time as in the high price scenario. The high CO_2 penalty, which cannot be fully compensated by CO_2 capture, has a particularly significant impact on lignite.
- If CCS can only be realised later, the increases in costs previously assumed for 2020 during the introduction of CCS would be postponed to later years (2025 or 2030). This would mean, however, that renewable energies would be able to produce energy more cheaply in both the low and high price scenarios as early as from when CCS is first introduced.
- In addition to the assumed increases in energy prices, the economics of CCS power plants are also affected by the fact that their full load hours will be halved by 2050, due to the assumed premise of the increased production of renewable energies.

4. Holistic assessment of environmental impacts

Only CO_2 emissions created directly at the power plant are generally included in the debate on CCS as a climate protection option. If a potential capture of 90 per cent is assumed, this would lead us to expect a high impact on climate. As already shown in the first RECCS study, however, it is also necessary to take a holistic approach with regard to environmental impacts that should additionally take the following aspects into account:

- CO_2 capture involves a considerable additional consumption of non-renewable resources, with all of the associated consequences;
- due to the additional consumption of primary energy, CO_2 emissions in the power plant process initially rise, so that the actual quantity of CO_2 avoided is considerably lower than the quantity of CO_2 captured (called the *avoidance efficiency* by Koornneef et al. (2008b))*;*
- when determining the *greenhouse gas avoidance efficiency*, the whole CCS chain, including the upstream chain of the individual energy and material flows, must be taken into account in addition to the power plant processes;
- political goals focus on a reduction in emissions of *all greenhouse gases*. Due to the additional consumption of primary energy and the other stages in the process chain, there would be a rise in non-CO_2 emissions, in particular, which cannot be collected by the capture process. It was shown in the previous study that greenhouse gas emissions from CCS power stations due to be operational by 2020 will only be reduced in total by around 68 to 87 per cent, depending on the technology (up to 95 per cent only in exceptional cases of specific combinations of technologies and fuels[79]);

[79] 95 per cent net reduction of greenhouse gases could be achieved with lignite-fired steam power plants equipped with oxyfuel technology if a 99.5 per cent CO_2 capture rate is possible.

- some of the other numerous environmental factors increase considerably (and can only be effectively reduced by pure oxygen combustion). This is also due to the additional consumption of energy.

As this analysis shows, when looking holistically at the environmental picture, CCS technology is in itself neither beneficial nor sustainable. It is the responsibility of politicians to deliberate about whether a reduction in CO_2 emissions can be reconciled with the consequences described here or whether other energy technologies without these disadvantages are preferable. Besides renewable energies, these include existing fossil technologies, such as CHP plants based on natural gas, which already achieve the emission targets set for the future for CCS technologies.

5. Storage site capacity and public acceptance

As investigations have shown, the availability of long-term, stable storage sites, in particular, will be pivotal in determining the acceptance of CCS technology by the general public. There is likely to be a groundswell of protest from bodies such as NGOs, churches and the federal state governments from the areas earmarked as potential storage locations. In terms of transport, the debate has focused on RWE's planned pipeline from Hürth to North Frisia, although the first exploration tests by utility companies were carried out in Brandenburg and, most prolifically, in Schleswig-Holstein. Compared to the first RECCS study, therefore, the range of stakeholders has been extended to political and social stakeholders from the storage regions. The issue of public acceptance has risen far higher up the agenda than was the case three years ago. If CCS technology should prove to be technically viable, commercially available and even competitive, in spite of the presented cost scenarios, the decisive factors are likely to be the question of the availability of suitable storage sites and gaining public acceptance of their use on a large scale.

Scientifically, the question of the availability of potential storage sites for CO_2 emissions from Germany ultimately remains unanswered. The scope of this analysis was, therefore, not restricted to Germany, but was extended to Germany's neighbours where there may be scope for their storing German CO_2 emissions. The objectives were:

- to systematically analyse and compare existing estimates of storage site capacities with regard to their methods and assumptions, and
- to present a conservative estimate, a lower limit, as a benchmark for potential investors and politicians.

The main findings of the analysis are that:

- there are significant uncertainties surrounding the information about storage potentials (this applies explicitly to the conservative calculation, too);
- the specific basic assumptions from the existing studies could not always be applied adequately to this analysis, thereby making it difficult to produce a comparative study;
- according to existing studies, the storage potential within Germany is estimated to be up to 44 billion tonnes;

- taking a cautious, conservative estimate, the available storage capacity must be assumed to be significantly limited (5 billion tonnes of CO_2 was estimated, assuming closed systems and a subsequent efficiency factor of 0.1 per cent for saline aquifers);
- in the event of higher demands, it would be necessary to switch storage to areas in British and Norwegian waters of the North Sea, where there is expected to be sufficient potential;
- even using the conservative estimate, however, the emissions projected in this scenario, which are intended to be realistic, calculate 1.2 billion tonnes of CO_2 up to 2050 for the power plant sector that could need storing, in addition to further industrial emissions;
- EOR (enhanced oil recovery) could act as an inroad for CCS in Europe, if sufficient CO_2 could be made available by 2020. However, this would not be appropriate as an independent climate protection option;
- guidelines for a standardised and documented estimate of storage potentials are required because huge deviations exist in the approach pursued by individual studies, both in their assumption of central parameters and, in particular, in the documentation of these assumptions.

The “storage cadastre”, currently being drawn up by the BGR, is expected to constitute a considerable improvement in terms of clarifying data availability, since all existing geological investigations at federal state level will be brought together. Nonetheless, considerable uncertainty will remain until potential storage sites for CO_2 are not investigated individually.

Regardless of the eventual realisable capacity, the question of whether this potential could be exploited quickly enough remains unanswered. It has not yet been explored whether there will be sufficient quantities of CO_2 in a short space of time, as might be expected from a constant flow from large-scale power plants, that can be injected into a storage site. Based on BGR’s assumptions on storage sites in Germany, (Gerling 2010) estimates the maximum quantity of CO_2 that can be injected annually to be 50 to 75 million tonnes. This amount would suffice for the “Realistisch I” scenario, but not for any larger capture quantities. For this reason, it is recommended that there is an investigation of the infrastructure required and the quantities of CO_2 to be transported and injected, using various capacity scenarios for storage sites (RECCS plus, GeoCapacity, BGR), coupled with emissions scenarios (for example from Chapter 10). The production capacity available to plants for the capture and injection of CO_2 should also be included in the timeline. There has already been a basic study of this for North Rhine-Westphalia in the present analyses (WI 2009). Such a study could be developed by using scenarios to show which CCS potential in Germany would realistically have to be available.

6. CCS legislation

A decisive factor affecting the introduction of CCS is the relevant legislation, since it affects the timescale of the implementation. The European “CCS Directive” is considered to be the framework for all activities along the CCS chain. In June 2009, the European Union adopted the CCS Directive, which is to be incorporated into the national law of all Member States within two years. This Directive, along with other modified legislation, constitutes a comprehensive policy for the use of CCS technology valid in all EU Member States that is suitable

for achieving the pursued objectives. By integrating the entire CCS process chain into the European emission trading system, a tool for CCS will be activated that can be used to provide incentives to investors from both an investment security and an economic perspective. The Directive does not provide guidelines on how authorities should prioritise between different competing projects requiring the same geological formation to be present (for instance, geothermal energy or gas storage versus CO_2 storage). Nor does it prescribe which project the respective authority should prioritise.

Regarding available applicable law in individual countries and the planned transposition of the EU Directive, it can be said that

- the applicable law is not suitable for capturing the whole CCS process chain, in particular with regard to storage;
- the prompt creation of a suitable legal framework for CCS is necessary to provide legal and investment security;
- given the gaps in the knowledge, a CCS law should provisionally only enable R&D and demonstration projects and then be scheduled for subsequent review;
- provisions in anticipation of the need to detect, assess and solve conflicts of interest as a result of a large-scale use of the CCS process should be accommodated.

11.3 CCS in the international focus

In view of the limitations presented here, the position of focusing on CCS as an option in the power plant sector while simultaneously retaining the current energy policy priorities (expansion of renewable energies and CHP, exhaustion of efficiency potentials and possibly extending the lifespan of nuclear power plants) is becoming increasingly untenable. Although most of the results from the present study relate to Germany, similar conclusions may well be applicable for the *rest of Europe,* in view of EU guidelines to expand renewable energies and increase energy efficiency.

Nevertheless, *globally,* CCS remains an important climate protection technology: coal-consuming countries such as China and India are increasingly moving centre stage into the debate, and these countries may not have the option of rapidly expanding renewable energies. For this reason, research, development and demonstration in the power plant sector continue to be important activities, as long as they are not at the expense of funding for renewable energies. But the questions set out above are also increasingly coming to the fore, drawing attention to the timeline: what potential does the fossil power plant mix offer in the medium to long term? Which power stations will possess the necessary criteria to make them eligible for retrofitting? Alternatively, should they be rebuilt as CCS power plants if the CCS chain is potentially only available for use from 2030? These questions will be explored in the follow-up project “CCS global”, which was launched at the end of 2009 in collaboration with Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH.

11.4 CCS in industry and in the use of biomass

In Germany, the debate is increasingly being directed towards alternative applications of CCS. Whereas politicians, utility companies and lobby groups still focus mainly on CCS in

the power plant sector, research institutes, advisory bodies and NGOs are increasingly emphasising that the capture of CO_2 at industrial point sources and biomass power plants outweigh this in importance (see the analysis of stakeholders in Chapter 5). These options for use have only been touched upon in the present study (Section 2.2), but should nevertheless be considered briefly here.

1. CO_2 capture at industrial point sources

Whereas only greenhouse gas emissions with a target of minus 80 per cent were usually considered in national climate scenarios, in light of higher reductions now being demanded (90 to 95 per cent by 2050), industry will also have to considerably reduce its emissions.

In general terms, steelworks, the glass industry, the cement industry, parts of the chemical industry and mineral oil and gas refineries are viewed as industrial point sources with a potential for CCS. In many processes, CO_2 is emitted in a highly concentrated state (3 to 25 per cent), and could therefore be separated more easily than from the flue gases of power stations (3 to 5 per cent). In addition, unlike with CCS in the power plant sector, in the industrial context there are virtually no alternative options available that could assist in a further reduction of CO_2 emissions. Industry can only resort to using electricity and heat from renewable energies, where they are used directly (for example, in electricity powered steelworks). In contrast, a significant share of emissions is process-immanent, and cannot be avoided by applying measures such as renewable energies. There is still a definite need for research into the fields of application of CCS in industry across all sectors.

There has not yet been any estimate of the CCS potential for industrial point sources in Germany, hence the proposal of the following research programme:

- For all process steps in which CO_2 is emitted but cannot be replaced directly by renewable energies, an investigation must be carried out into which alternative methods have already been applied, together with the timeline, costs and reduction rates involved in developing such methods.
- From the remaining processes, we must then identify which processes emit CO_2 in such a concentrated state that it can be separated and then linked to economic estimates.
- With regard to alternative possibilities, there should be investigations into the extent to which other products and processes can be devised and applied that can lead to a decreased occurrence of CO_2 emissions (for example, through enhanced technology, higher efficiency, other raw materials, etc.).

2. CO_2 capture at biomass power plants

The application of CCS in biomass plants (power and heat production, fuels) is of interest because “negative” CO_2 emissions can be achieved. By separating the CO_2 absorbed by plants during growth, CO_2 could not only be avoided, but extracted long-term from the atmosphere. This could become relevant if it proves to be impossible to achieve the set reduction targets in other areas. The Bellona scenario, for instance, calculates for “carbon negative energy” an 18 per cent share in the total reductions in 2050 (Bellona 2008); in the current scenarios with the aim of stabilising greenhouse gas emissions at 400 ppm CO_2 equivalents, “the use of biomass in combination with CCS plays a crucial role,” whereby the biomass potential determines the costs of this climate protection option (Edenhofer et al. 2010).

Whereas also (Vuuren et al. 2007) and (Schellnhuber 2009) point to relevant scenarios, there is a need for research into the specific CCS potential that could be implemented in Germany. To this end, it must be taken into account that

- biomass plants for generating electricity currently have a maximum capacity of 30 MW_{el}, and the degree of utilisation is only around 20 per cent, meaning that there is considerable potential for development to link them to an option that is primarily applicable on a large scale, such as CO_2 capture;
- here, again, not only avoided CO_2 emissions, but all of the environmental impacts that occur along the whole cultivation and use chain must be taken into account (for instance, the considerably more powerful greenhouse gas N_2O is created in this case);
- the use of biomass for energy purposes is associated with a multitude of other problems, such as deforestation, monocultures, interactions with the agri-food sector, water shortages or, in the long term, a lack of nutrients in soils.

Due to the limited availability of suitable CO_2 storage sites, the potential use of CCS should mainly occur in the industrial sector and for biomass plants. So far, there are no clear, reliable figures for the capacities that could in fact be used in suitable geological formations. If conservative estimates should turn out to be realistic, this space should initially be reserved for these applications. For biomass, however, these storage potentials would only be used in around 40 years. Any usage strategy that allocates them without respect for future requirements with instead cost efficiency being the focus, i.e. along the lines of “whoever comes first will receive the most favourable storage complexes for free” must be rejected in favour of intergenerational justice. Storage complexes are a scarce good; parallels can be drawn between them and the earth’s atmosphere as a store for greenhouse gas emissions.

The separation of CO_2 in industry and for biomass plants would have the added advantage that they generally create fewer emissions than large power stations, enabling the gases to be injected into smaller storage sites. With power plants, however, between 100 and 400 megatonnes can be emitted in their lifetime, meaning that emissions from such plants will rarely be deposited at one single storage site.

Based on the results of this study, it is therefore recommended that major attention is given first to the two options of industry and biomass, rather than to power plants, and that their CCS potential for Germany is explored.

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13 Appendix

13.1 Appendix 1: Key data of the cost calculation (Chapter 9)

Tab. 13-1 Price trends for fuels and CO_2 allowances under three different scenarios: A (considerable), B (moderate) and C (very low)

		2005	2010	2015	**2020**	2025	**2030**	2035	2040	2045	**2050**
CO2 penalty											
Price trajectory A (considerable)	€/t		24	32	39	45	50	55	60	65	70
Price trajectory B (moderate)	€/t		20	25	30	33	35	38	40	43	45
Price trajectory C (very low)	€/t		15	18	20	22	23	25	26	27	28
Price trajectory AA (Fuel price trajectory A, CO2 penalty trajectory A)											
without CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	7.83	9.17	10.67	12.2	13.79	15.2	16.53	17.53	18.52
Hard coal	$€_{2005}/GJ_{th}$	2.1	3.91	4.59	5.33	6.1	6.89	7.72	8.54	9.195	9.85
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	1.12	1.2	1.25	1.3	1.37	1.44	1.5	1.575	1.65
with CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	9.177	11	12.86	14.7	16.6	18.2	19.9	21.17	22.45
Hard coal	$€_{2005}/GJ_{th}$	2.1	6.163	7.59	8.992	10.3	11.58	12.9	14.17	15.3	16.42
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	3.82	4.8	5.638	6.36	6.995	7.62	8.25	8.888	9.525
Price trajectory AB (Fuel price trajectory A, CO2 penalty trajectory B)											
without CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	6.92	7.65	8.43	9.22	9.99	10.6	11.26	11.68	12.1
Hard coal	$€_{2005}/GJ_{th}$	2.1	3.46	3.82	4.22	4.61	5	5.32	5.63	5.84	6.05
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	1.12	1.17	1.22	1.27	1.32	1.37	1.41	1.455	1.5
with CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	8.042	9.05	10.11	11.1	11.95	12.7	13.5	14.06	14.63
Hard coal	$€_{2005}/GJ_{th}$	2.1	5.338	6.17	7.037	7.71	8.286	8.84	9.386	9.83	10.28
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	3.37	3.98	4.595	4.98	5.258	5.58	5.91	6.236	6.563
Price trajectory AC (Fuel price trajectory A, CO2 penalty trajectory C)											
Natural gas	$€_{2005}/GJ_{th}$	4.66	8.672	10.2	11.79	13.4	15.08	16.5	17.99	19.04	20.09
Hard coal	$€_{2005}/GJ_{th}$	2.1	5.318	6.28	7.208	8.12	9.049	10	10.98	11.73	12.48
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	2.808	3.23	3.5	3.72	3.958	4.19	4.425	4.613	4.8
Price trajectory CA (Fuel price trajectory C, CO2 penalty trajectory A)											
Natural gas	$€_{2005}/GJ_{th}$	4.66	7.607	8.33	8.998	9.7	10.32	10.9	11.46	11.95	12.44
Hard coal	$€_{2005}/GJ_{th}$	2.1	5.283	6.17	6.962	7.71	8.344	8.96	9.583	10.15	10.72
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	3.81	4.74	5.558	6.28	6.875	7.48	8.08	8.673	9.265
Price trajectory CC (Fuel price trajectory C, CO2 penalty trajectory C)											
without CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	6.26	6.53	6.81	7.17	7.51	7.8	8.09	8.3	8.51
Hard coal	$€_{2005}/GJ_{th}$	2.1	3.03	3.17	3.3	3.48	3.65	3.8	3.95	4.05	4.15
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	1.11	1.14	1.17	1.22	1.25	1.29	1.33	1.36	1.39
with CO2 penalty											
Natural gas	$€_{2005}/GJ_{th}$	4.66	7.102	7.54	7.932	8.38	8.801	9.17	9.549	9.815	10.08
Hard coal	$€_{2005}/GJ_{th}$	2.1	4.438	4.86	5.178	5.5	5.809	6.1	6.391	6.585	6.779
Lignite (domestic)	$€_{2005}/GJ_{th}$	1.05	2.798	3.17	3.42	3.64	3.838	4.05	4.255	4.398	4.54

Source: Authors' own design

Tab. 13-2 Electricity generating costs for fossil fuel-fired power plants with/without CCS for different energy source and CO_2 price trajectories A/C (considerable/very low) and C/A (very low/considerable)

Natural Gas (CC)	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
	Trajectory A/C, w/o CCS					*Trajectory C/A, w/o CCS*				
Investment	0.61	0.63	0.68	0.79	0.87	0.61	0.63	0.68	0.79	0.87
Operation/Maintenance	0.61	0.69	0.74	0.81	0.89	0.61	0.69	0.74	0.81	0.89
Fuel	4.78	6.40	8.14	9.60	10.75	3.82	4.09	4.43	4.70	4.94
CO2 penalty	0.51	0.67	0.76	0.85	0.91	0.82	1.31	1.66	1.95	2.28
Total	6.50	8.40	10.33	12.05	13.43	5.85	6.72	7.52	8.25	8.99
	Trajectory A/C, with CCS					*Trajectory C/A, with CCS*				
Investment		1.43	1.54	1.48	1.63		1.43	1.54	1.48	1.63
Operation/Maintenance		1.09	1.18	1.27	1.39		1.09	1.18	1.27	1.39
Fuel		7.53	9.55	10.82	12.12		4.81	5.20	5.30	5.57
CO2 penalty		0.10	0.11	0.08	0.08		0.19	0.23	0.18	0.21
Transport&Storage		0.20	0.20	0.18	0.18		0.20	0.20	0.18	0.18
Total		10.35	12.57	13.83	15.41		7.71	8.35	8.40	8.98
Difference without/with CCS		1.95	2.24	1.78	1.98		0.99	0.83	0.15	0.00

Hard coal (steam)	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
	Trajectory A/C, w/o CCS					*Trajectory C/A, w/o CCS*				
Investment	1.39	1.51	1.54	1.78	1.96	1.39	1.51	1.54	1.78	1.96
Operation/Maintenance	0.86	0.98	1.05	1.14	1.25	0.86	0.98	1.05	1.14	1.25
Fuel	2.99	3.92	4.91	5.91	6.82	2.32	2.42	2.60	2.73	2.87
CO2 penalty	1.08	1.38	1.54	1.69	1.82	1.73	2.69	3.35	3.90	4.55
Total	6.33	7.78	9.04	10.52	11.85	6.30	7.60	8.54	9.56	10.64
	Trajectory A/C, with CCS					*Trajectory C/A, with CCS*				
Investment		2.77	2.90	3.17	3.49		2.77	2.90	3.17	3.49
Operation/Maintenance		1.63	1.75	1.87	2.06		1.63	1.75	1.87	2.06
Fuel		4.80	5.98	6.99	8.06		2.97	3.17	3.23	3.40
CO2 penalty		0.20	0.22	0.18	0.19		0.40	0.49	0.41	0.48
Transport&Storage		0.40	0.40	0.36	0.36		0.40	0.40	0.36	0.36
Total		9.80	11.26	12.57	14.16		8.17	8.71	9.05	9.79
Difference without/with CCS		2.02	2.22	2.04	2.31		0.57	0.17	-0.51	-0.85

Hard coal (IGCC)	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
	Trajectory A/C, w/o CCS					*Trajectory C/A, w/o CCS*				
Investment	2.09	2.06	2.01	2.18	2.28	2.09	2.06	2.01	2.18	2.28
Operation/Maintenance	0.94	1.07	1.09	1.24	1.30	0.94	1.07	1.09	1.24	1.30
Fuel	2.93	3.84	4.31	5.69	6.13	2.27	2.38	2.46	2.63	2.70
CO2 penalty	1.06	1.35	1.42	1.63	1.69	1.69	2.64	2.98	3.76	4.07
Total	7.02	8.32	8.83	10.74	11.40	7.00	8.15	8.54	9.81	10.35
	Trajectory A/C, with CCS					*Trajectory C/A, with CCS*				
Investment		3.17	3.25	3.37	3.71		3.17	3.25	3.37	3.71
Operation/Maintenance		1.72	1.86	1.97	2.17		1.72	1.86	1.97	2.17
Fuel		4.57	5.64	6.68	7.71		2.83	2.99	3.09	3.25
CO2 penalty		0.19	0.21	0.17	0.19		0.38	0.46	0.40	0.46
Transport&Storage		0.40	0.40	0.36	0.36		0.40	0.40	0.36	0.36
Total		10.05	11.35	12.56	14.13		8.50	8.95	9.19	9.95
Difference without/with CCS		1.73	2.52	1.82	2.73		0.35	0.41	-0.62	-0.40

Lignite (steam)	**2010**	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
	Trajectory A/C, w/o CCS					*Trajectory C/A, w/o CCS*				
Investment	1.64	1.74	1.81	2.08	2.29	1.64	1.74	1.81	2.08	2.29
Operation/Maintenance	1.01	1.13	1.24	1.33	1.46	1.01	1.13	1.24	1.33	1.46
Fuel	0.90	0.98	1.04	1.10	1.19	0.89	0.92	0.95	0.98	1.00
CO2 penalty	1.35	1.76	1.96	2.15	2.27	2.16	3.43	4.26	4.96	5.67
Total	4.89	5.62	6.05	6.66	7.21	5.70	7.23	8.26	9.34	10.42
	Trajectory A/C, with CCS					*Trajectory C/A, with CCS*				
Investment		3.22	3.40	3.70	4.08		3.22	3.40	3.70	4.08
Operation/Maintenance		1.88	2.05	2.19	2.41		1.88	2.05	2.19	2.41
Fuel		1.32	1.39	1.38	1.49		1.24	1.27	1.23	1.25
CO2 penalty		0.29	0.31	0.27	0.28		0.56	0.68	0.62	0.71
Transport&Storage		0.40	0.40	0.36	0.36		0.40	0.40	0.36	0.36
Total		7.11	7.55	7.90	8.61		7.30	7.80	8.10	8.80
Difference without/with CCS		1.49	1.50	1.24	1.40		0.07	-0.46	-1.25	-1.62

All quantities given in ct/kWh$_{el}$
First letter: Fuel price trajectory / Second letter: CO2 price trajectory
A = considerable, C = very low

Source: Authors' own design

Tab. 13-3 Future cost trend of electricity-generating renewable energy technologies (new plants) and the mean of the whole mix of renewable energies (with/without photovoltaics)

	Wind			Hydro	Photo-	Geo-	Import	Solid	Biogas	Mean	Mean w/o
	total	offshore [a)]	onshore [b)]		voltaics	thermal		Biomass			photovolt.
2000	0.094		0.094	0.047	0.735			0.100	0.105	0.105	0.097
2001	0.093		0.093	0.047	0.690			0.100	0.105	0.102	0.094
2002	0.091		0.091	0.047	0.649			0.100	0.114	0.099	0.093
2003	0.090		0.090	0.056	0.606			0.100	0.120	0.100	0.093
2004	0.088		0.088	0.057	0.568			0.100	0.127	0.108	0.093
2005	0.088		0.088	0.059	0.535	0.706		0.100	0.130	0.113	0.093
2006	0.087		0.087	0.066	0.502	0.703		0.100	0.129	0.117	0.093
2007	0.086	0.166	0.086	0.065	0.462	0.471		0.101	0.128	0.114	0.091
2008	0.086	0.166	0.085	0.066	0.426	0.390		0.104	0.127	0.117	0.093
2009	0.089	0.159	0.085	0.063	0.390	0.284		0.103	0.124	0.120	0.094
2010	0.092	0.147	0.084	0.062	0.354	0.211		0.105	0.123	0.121	0.096
2011	0.094	0.140	0.083	0.065	0.319	0.192		0.106	0.121	0.122	0.098
2012	0.098	0.132	0.081	0.067	0.289	0.172		0.107	0.119	0.122	0.100
2013	0.100	0.125	0.080	0.068	0.258	0.160		0.107	0.118	0.120	0.100
2014	0.098	0.118	0.078	0.070	0.235	0.148		0.106	0.117	0.116	0.099
2015	0.094	0.111	0.077	0.071	0.212	0.135		0.106	0.115	0.111	0.096
2016	0.089	0.103	0.075	0.071	0.189	0.107		0.106	0.113	0.106	0.093
2017	0.086	0.098	0.074	0.071	0.172	0.097		0.107	0.111	0.102	0.091
2018	0.083	0.093	0.072	0.071	0.155	0.075	0.087	0.106	0.108	0.097	0.088
2019	0.079	0.087	0.071	0.071	0.143	0.068	0.084	0.103	0.106	0.092	0.085
2020	0.076	0.082	0.069	0.070	0.137	0.060	0.082	0.099	0.103	0.089	0.082
2030	0.065	0.068	0.062	0.071	0.106	0.049	0.072	0.092	0.097	0.074	0.070
2040	0.058	0.058	0.058	0.069	0.097	0.050	0.064	0.082	0.090	0.065	0.062
2050	0.053	0.052	0.054	0.067	0.092	0.051	0.061	0.070	0.083	0.060	0.057

All quantities given in EUR_{2005}/kWh_{el}

[a)] 5 MW class, 30 m depth, including grid connection, without grid extension

[b)] for growth from 2001

Source: Authors' own design

13.2 Appendix 2: Key data of variants 1 to 6 of scenario CCS-EE/KWK (Chapter 10)

Tab. 13-4 Key data of the scenario variant “Maximal-theoretisch”

Scenario variant:	MAXIMAL - THEORETISCH						
CCS proportions new plants	CPS =	1.00	CHPP =	1.00			
CCS proportions retrofitting	CPS =	1.00	CHPP =	1.00			
	Capacity of power plants with CO2 capture ++) from 2021; total value					with 2007 renewables data	
	New up to	New from 2020					
Year	2020	2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**5.60**	**7.76**	**11.67**	**15.57**	**17.74**	**19.91**
-hard coal/other solid fuels	10.82	3.09	4.18	6.63	9.08	10.52	11.96
-brown coal	6.32	2.52	3.58	4.10	4.61	5.34	6.07
-natural gas/oil/other gases	3.14	0.00	0.00	0.94	1.88	1.88	1.88
-nuclear power	0.00						
Public CHPP	**5.46**	**1.79**	**2.89**	**5.69**	**8.49**	**10.29**	**12.08**
- CHPP brown coal	0.33	0.00	0.35	0.74	1.13	2.17	3.20
- CHPP (hard coal, waste)	4.49	1.43	2.18	3.98	5.78	6.47	7.17
- CHPP (natural gas + oil)	0.64	0.36	0.36	0.97	1.58	1.65	1.71
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**1.44**	**3.32**	**5.05**	**6.79**	**7.79**	**8.79**
- CHPP (hard coal)	1.40	1.08	2.18	3.15	4.13	4.85	5.58
- CHPP (natural gas, oil)	0.51	0.36	1.14	1.90	2.66	2.94	3.21
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**8.83**	**13.97**	**22.41**	**30.85**	**35.81**	**40.78**
- hard coal/other solid fuels	16.71	5.60	8.53	13.76	18.98	21.84	24.70
- brown coal	6.65	2.52	3.93	4.84	5.74	7.50	9.27
- natural gas/oil/other gases	5.69	0.72	1.50	3.81	6.12	6.47	6.81
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**3.23**	**6.21**	**10.74**	**15.28**	**18.07**	**20.87**
CHPP brown coal	0.33	0.00	0.35	0.74	1.13	2.17	3.20
CHPP hard coal	5.89	2.51	4.36	7.13	9.90	11.32	12.74
CHPP natural gas	1.15	0.72	1.50	2.87	4.24	4.59	4.93
Additional capacity required for CCS (prop. additional requirement of fuel)		**2.09**	**3.29**	**5.07**	**6.85**	**8.07**	**9.28**
- hard coal/other solid fuels		1.16	1.77	2.85	3.94	4.53	5.12
- brown coal		0.80	1.26	1.55	1.83	2.40	2.96
- natural gas/oil/other gases		0.13	0.26	0.67	1.08	1.14	1.20

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**33.9**	**46.8**	**63.9**	**80.1**	**86.5**	**91.6**
- hard coal/other solid fuels	0	15.8	21.3	33.1	44.5	47.9	50.2
- brown coal	0	18.1	25.5	27.9	30.0	33.9	37.6
- natural gas/oil/other gases	0	0.0	0.0	2.9	5.6	4.7	3.8
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**5.0**	**7.9**	**15.8**	**23.6**	**27.6**	**31.3**
- hard coal/other solid fuels	0	3.7	5.7	10.3	15.0	16.2	17.3
- brown coal	0	0.0	1.0	2.0	3.1	5.6	8.0
- natural gas/oil/other gases	0	1.3	1.3	3.4	5.5	5.8	6.0
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**4.1**	**9.3**	**13.9**	**18.2**	**20.8**	**23.5**
- hard coal/other solid fuels	0	3.0	5.9	8.4	10.7	12.6	14.5
- natural gas/oil/other gases	0	1.1	3.4	5.5	7.4	8.2	9.0
Total power generation, TWh/a	**0.0**	**42.9**	**64.0**	**93.6**	**121.9**	**134.9**	**146.4**
- hard coal/other solid fuels	0	22.5	32.8	51.8	70.2	76.7	82.0
- brown coal	0	18.1	26.4	29.9	33.0	39.5	45.6
- natural gas/oil/other gases	0	2.3	4.7	11.8	18.6	18.7	18.8
Moderate utilisation, h/a		4861	4579	4175	3951	3767	3589
Proportion of total power generation; %		7.2	10.7	15.3	19.9	21.5	23.1

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	13.0	19.0	30.0	40.6	44.4	47.4
- brown coal	0.0	0.0	0.0	0.0	12.8	18.7	21.2	23.4	28.0	32.3
- natural gas	0.0	0.0	0.0	0.0	0.7	1.3	3.4	5.4	5.4	5.4
Total	**0.0**	**0.0**	**0.0**	**0.0**	**26.5**	**39.1**	**54.5**	**69.3**	**77.7**	**85.1**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**243**	**187**	**134**	**80.4**	**45.0**	**10.5**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct Emiss. g/kWh el	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338		682	865	**0.88**	104	**761**	**578**
- brown coal			403		849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	34	50	78	106	116	124
- brown coal				0.0	44	64	72	80	96	110
- natural gas				0.0	2	5	13	20	20	20
Total				**0.0**	**80**	**118**	**163**	**206**	**231**	**254**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	17.1	25.0	39.5	53.5	58.4	62.4
- brown coal				0.0	18.7	27.4	30.9	34.2	40.9	47.2
- natural gas				0.0	0.9	1.7	4.3	6.8	6.9	6.9
Total				**0.0**	**36.7**	**54.1**	**74.7**	**94.5**	**106.1**	**116.5**

Source: Authors' own design

Tab. 13-5 Key data of the scenario variant “Maximal-realistisch”

Scenario variant:	MAXIMAL - REALISTISCH						
CCS proportions new plants	CPS =	1.00	CHPP =	0.65			
CCS proportions retrofitting	CPS =	0.75	CHPP =	0.35			
	Capacity of power plants with CO2 capture ++) from 2021; total value				with 2007 renewables data		
	New up to	New from 2020					
Year	2020	2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**5.60**	**7.76**	**10.36**	**12.96**	**15.53**	**18.11**
-hard coal/other solid fuels	10.82	3.09	4.18	5.91	7.64	8.90	10.16
-brown coal	6.32	2.52	3.58	3.74	3.90	4.98	6.07
-natural gas/oil/other gases	3.14	0.00	0.00	0.71	1.41	1.65	1.88
-nuclear power	0.00						
Public CHPP	**5.46**	**1.17**	**1.88**	**3.16**	**4.45**	**5.48**	**6.51**
- CHPP brown coal	0.33	0.00	0.23	0.44	0.66	1.32	1.98
- CHPP (hard coal, waste)	4.49	0.93	1.41	2.12	2.82	3.16	3.50
- CHPP (natural gas + oil)	0.64	0.23	0.23	0.60	0.96	1.00	1.03
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**0.93**	**2.16**	**3.10**	**4.04**	**4.65**	**5.25**
- CHPP (hard coal)	1.40	0.70	1.42	1.93	2.43	2.87	3.32
- CHPP (natural gas, oil)	0.51	0.23	0.74	1.17	1.61	1.77	1.94
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**7.70**	**11.80**	**16.62**	**21.44**	**25.66**	**29.87**
- hard coal/other solid fuels	16.71	4.72	7.01	9.95	12.90	14.93	16.97
- brown coal	6.65	2.52	3.81	4.19	4.56	6.31	8.05
- natural gas/oil/other gases	5.69	0.47	0.98	2.48	3.98	4.42	4.85
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**2.10**	**4.04**	**6.26**	**8.49**	**10.13**	**11.76**
CHPP brown coal	0.33	0.00	0.23	0.44	0.66	1.32	1.98
CHPP hard coal	5.89	1.63	2.83	4.05	5.26	6.03	6.81
CHPP natural gas	1.15	0.47	0.98	1.77	2.57	2.77	2.97
Additional capacity required for CCS (prop. additional requirement of fuel)		**1.86**	**2.84**	**3.84**	**4.83**	**5.89**	**6.95**
- hard coal/other solid fuels		0.98	1.45	2.06	2.67	3.10	3.52
- brown coal		0.80	1.22	1.34	1.46	2.01	2.57
- natural gas/oil/other gases		0.08	0.17	0.44	0.70	0.78	0.86

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**33.9**	**46.8**	**57.2**	**67.1**	**76.3**	**84.0**
- hard coal/other solid fuels	0	15.8	21.3	29.5	37.4	40.5	42.7
- brown coal	0	18.1	25.5	25.5	25.4	31.7	37.6
- natural gas/oil/other gases	0	0.0	0.0	2.2	4.2	4.1	3.8
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**3.2**	**5.1**	**8.8**	**12.5**	**14.8**	**17.0**
- hard coal/other solid fuels	0	2.4	3.7	5.5	7.3	7.9	8.4
- brown coal	0	0.0	0.6	1.2	1.8	3.4	5.0
- natural gas/oil/other gases	0	0.8	0.8	2.1	3.4	3.5	3.6
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**2.7**	**6.1**	**8.5**	**10.8**	**12.4**	**14.0**
- hard coal/other solid fuels	0	2.0	3.8	5.1	6.3	7.5	8.6
- natural gas/oil/other gases	0	0.7	2.2	3.4	4.5	5.0	5.4
Total power generation, TWh/a	**0.0**	**39.8**	**57.9**	**74.5**	**90.4**	**103.5**	**115.1**
- hard coal/other solid fuels	0	20.1	28.8	40.2	51.1	55.9	59.7
- brown coal	0	18.1	26.1	26.7	27.2	35.1	42.6
- natural gas/oil/other gases	0	1.5	3.0	7.7	12.1	12.6	12.8
Moderate utilisation, h/a		5162	4911	4484	4214	4036	3853
Proportion of total power generation; %		6.7	9.7	12.2	14.8	16.5	18.1

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	11.6	16.7	23.2	29.6	32.3	34.5
- brown coal	0.0	0.0	0.0	0.0	12.8	18.5	18.9	19.2	24.8	30.1
- natural gas	0.0	0.0	0.0	0.0	0.4	0.9	2.2	3.5	3.6	3.7
Total	**0.0**	**0.0**	**0.0**	**0.0**	**24.9**	**36.0**	**44.3**	**52.3**	**60.8**	**68.3**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**244**	**190**	**144**	**97.5**	**61.9**	**27.3**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338	Emiss.	682	865	**0.88**	104	**761**	**578**
- brown coal			403	g/kWh el	849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	30	43	61	77	84	90
- brown coal				0.0	44	63	65	66	85	103
- natural gas				0.0	2	3	8	13	13	14
Total				**0.0**	**76**	**110**	**133**	**156**	**183**	**207**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	15.3	21.9	30.6	38.9	42.5	45.4
- brown coal				0.0	18.7	27.0	27.6	28.1	36.3	44.1
- natural gas				0.0	0.6	1.1	2.8	4.4	4.6	4.7
Total				**0.0**	**34.6**	**50.0**	**61.0**	**71.4**	**83.5**	**94.2**

Source: Authors' own design

Tab. 13-6 Key data of the scenario variant “Maximal-Neu”

Scenario variant:	MAXIMAL - NEU						
CCS proportions new plants	CPS =	1.00	CHPP =	0.65			
CCS proportions retrofitting	CPS =	0.00	CHPP =	0.00			
	Capacity of power plants with CO2 capture ++) from 2021; total value					with 2007 renewables data	
Year	New up to 2020	New from 2020 2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**5.60**	**7.76**	**6.44**	**5.11**	**8.91**	**12.71**
-hard coal/other solid fuels	10.82	3.09	4.18	3.75	3.32	4.04	4.76
-brown coal	6.32	2.52	3.58	2.69	1.79	3.93	6.07
-natural gas/oil/other gases	3.14	0.00	0.00	0.00	0.00	0.94	1.88
-nuclear power	0.00						
Public CHPP	**5.46**	**1.17**	**1.88**	**2.53**	**3.19**	**4.07**	**4.95**
- CHPP brown coal	0.33	0.00	0.23	0.40	0.57	1.22	1.87
- CHPP (hard coal, waste)	4.49	0.93	1.41	1.58	1.74	1.94	2.14
- CHPP (natural gas + oil)	0.64	0.23	0.23	0.56	0.88	0.91	0.93
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**0.93**	**2.16**	**2.89**	**3.61**	**4.16**	**4.72**
- CHPP (hard coal)	1.40	0.70	1.42	1.78	2.15	2.55	2.95
- CHPP (natural gas, oil)	0.51	0.23	0.74	1.10	1.47	1.61	1.76
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**7.70**	**11.80**	**11.86**	**11.92**	**17.14**	**22.37**
- hard coal/other solid fuels	16.71	4.72	7.01	7.11	7.21	8.53	9.85
- brown coal	6.65	2.52	3.81	3.09	2.36	5.15	7.94
- natural gas/oil/other gases	5.69	0.47	0.98	1.66	2.35	3.46	4.58
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**2.10**	**4.04**	**5.42**	**6.81**	**8.23**	**9.66**
CHPP brown coal	0.33	0.00	0.23	0.40	0.57	1.22	1.87
CHPP hard coal	5.89	1.63	2.83	3.36	3.88	4.49	5.09
CHPP natural gas	1.15	0.47	0.98	1.66	2.35	2.52	2.69
Additional capacity required for CCS (prop. additional requirement of fuel)		**1.86**	**2.84**	**2.75**	**2.66**	**4.02**	**5.39**
- hard coal/other solid fuels		0.98	1.45	1.47	1.49	1.77	2.04
- brown coal		0.80	1.22	0.99	0.75	1.64	2.54
- natural gas/oil/other gases		0.08	0.17	0.29	0.41	0.61	0.81

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**33.9**	**46.8**	**37.0**	**27.9**	**45.7**	**61.4**
- hard coal/other solid fuels	0	15.8	21.3	18.7	16.3	18.4	20.0
- brown coal	0	18.1	25.5	18.3	11.6	24.9	37.6
- natural gas/oil/other gases	0	0.0	0.0	0.0	0.0	2.4	3.8
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**3.2**	**5.1**	**7.2**	**9.2**	**11.2**	**13.1**
- hard coal/other solid fuels	0	2.4	3.7	4.1	4.5	4.9	5.2
- brown coal	0	0.0	0.6	1.1	1.5	3.2	4.7
- natural gas/oil/other gases	0	0.8	0.8	2.0	3.1	3.2	3.3
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**2.7**	**6.1**	**7.9**	**9.7**	**11.1**	**12.6**
- hard coal/other solid fuels	0	2.0	3.8	4.7	5.6	6.6	7.7
- natural gas/oil/other gases	0	0.7	2.2	3.2	4.1	4.5	4.9
Total power generation, TWh/a	**0.0**	**39.8**	**57.9**	**52.1**	**46.7**	**68.0**	**87.1**
- hard coal/other solid fuels	0	20.1	28.8	27.6	26.4	29.9	32.8
- brown coal	0	18.1	26.1	19.4	13.2	28.1	42.3
- natural gas/oil/other gases	0	1.5	3.0	5.2	7.2	10.1	12.0
Moderate utilisation, h/a		5162	4911	4394	3923	3969	3893
Proportion of total power generation; %		6.7	9.7	8.7	7.6	10.7	13.7

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	11.6	16.7	15.9	15.3	17.3	19.0
- brown coal	0.0	0.0	0.0	0.0	12.8	18.5	13.7	9.3	19.9	29.9
- natural gas	0.0	0.0	0.0	0.0	0.4	0.9	1.5	2.1	2.9	3.4
Total	**0.0**	**0.0**	**0.0**	**0.0**	**24.9**	**36.0**	**31.1**	**26.6**	**40.1**	**52.3**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**244**	**190**	**157**	**123.1**	**82.6**	**43.2**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct Emiss. g/kWh el	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338		682	865	**0.88**	104	**761**	**578**
- brown coal			403		849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	30	43	42	40	45	49
- brown coal				0.0	44	63	47	32	68	102
- natural gas				0.0	2	3	5	8	11	13
Total				**0.0**	**76**	**110**	**94**	**79**	**124**	**165**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	15.3	21.9	21.0	20.1	22.7	25.0
- brown coal				0.0	18.7	27.0	20.0	13.6	29.1	43.8
- natural gas				0.0	0.6	1.1	1.9	2.6	3.7	4.4
Total				**0.0**	**34.6**	**50.0**	**42.9**	**36.3**	**55.5**	**73.1**

Source: Authors' own design

Tab. 13-7 Key data of the scenario variant “Realistisch I”

Scenario variant:	REALISTISCH I						
CCS proportions new plants	CPS =	0.75	CHPP =	0.40			
CCS proportions retrofitting	CPS =	0.40	CHPP =	0.20			
	Capacity of power plants with CO2 capture ++) from 2021; total value					with 2007 renewables data	
	New up to	New from 2020					
Year	2020	2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**4.20**	**5.82**	**6.92**	**8.02**	**10.21**	**12.41**
-hard coal/other solid fuels	10.82	2.32	3.13	3.96	4.80	5.62	6.45
-brown coal	6.32	1.89	2.69	2.58	2.47	3.51	4.55
-natural gas/oil/other gases	3.14	0.00	0.00	0.38	0.75	1.08	1.41
-nuclear power	0.00						
Public CHPP	**5.46**	**0.72**	**1.15**	**1.92**	**2.68**	**3.31**	**3.94**
- CHPP brown coal	0.33	0.00	0.14	0.27	0.40	0.81	1.22
- CHPP (hard coal, waste)	4.49	0.57	0.87	1.28	1.69	1.89	2.09
- CHPP (natural gas + oil)	0.64	0.14	0.14	0.37	0.59	0.61	0.63
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**0.57**	**1.33**	**1.90**	**2.47**	**2.84**	**3.21**
- CHPP (hard coal)	1.40	0.43	0.87	1.18	1.49	1.75	2.02
- CHPP (natural gas, oil)	0.51	0.14	0.46	0.72	0.98	1.08	1.18
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**5.49**	**8.30**	**10.74**	**13.17**	**16.36**	**19.56**
- hard coal/other solid fuels	16.71	3.32	4.88	6.42	7.97	9.27	10.57
- brown coal	6.65	1.89	2.83	2.85	2.87	4.32	5.77
- natural gas/oil/other gases	5.69	0.29	0.60	1.46	2.32	2.78	3.23
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**1.29**	**2.48**	**3.82**	**5.15**	**6.15**	**7.15**
CHPP brown coal	0.33	0.00	0.14	0.27	0.40	0.81	1.22
CHPP hard coal	5.89	1.00	1.74	2.46	3.18	3.65	4.12
CHPP natural gas	1.15	0.29	0.60	1.09	1.57	1.69	1.81
Additional capacity required for CCS (prop. additional requirement of fuel)		**1.34**	**2.02**	**2.50**	**2.98**	**3.79**	**4.60**
- hard coal/other solid fuels		0.69	1.01	1.33	1.65	1.92	2.19
- brown coal		0.60	0.90	0.91	0.92	1.38	1.84
- natural gas/oil/other gases		0.05	0.11	0.26	0.41	0.49	0.57

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**25.4**	**35.1**	**38.5**	**41.8**	**50.6**	**58.1**
- hard coal/other solid fuels	0	11.8	16.0	19.8	23.5	25.6	27.1
- brown coal	0	13.6	19.1	17.5	16.1	22.3	28.2
- natural gas/oil/other gases	0	0.0	0.0	1.2	2.3	2.7	2.8
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**2.0**	**3.2**	**5.4**	**7.5**	**9.0**	**10.3**
- hard coal/other solid fuels	0	1.5	2.3	3.3	4.4	4.7	5.0
- brown coal	0	0.0	0.4	0.7	1.1	2.1	3.0
- natural gas/oil/other gases	0	0.5	0.5	1.3	2.1	2.1	2.2
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**1.6**	**3.7**	**5.2**	**6.6**	**7.6**	**8.6**
- hard coal/other solid fuels	0	1.2	2.4	3.1	3.9	4.6	5.3
- natural gas/oil/other gases	0	0.4	1.4	2.1	2.8	3.0	3.3
Total power generation, TWh/a	**0.0**	**29.0**	**41.9**	**49.1**	**56.0**	**67.1**	**77.0**
- hard coal/other solid fuels	0	14.5	20.6	26.3	31.8	34.9	37.4
- brown coal	0	13.6	19.5	18.3	17.1	24.4	31.2
- natural gas/oil/other gases	0	0.9	1.9	4.5	7.1	7.9	8.3
Moderate utilisation, h/a		5283	5051	4573	4250	4104	3936
Proportion of total power generation; %		4.9	7.0	8.1	9.2	10.6	12.1

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	8.4	11.9	15.2	18.4	20.2	21.6
- brown coal	0.0	0.0	0.0	0.0	9.6	13.8	12.9	12.1	17.3	22.1
- natural gas	0.0	0.0	0.0	0.0	0.3	0.5	1.3	2.0	2.3	2.4
Total	**0.0**	**0.0**	**0.0**	**0.0**	**18.3**	**26.2**	**29.4**	**32.5**	**39.7**	**46.1**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**251**	**200**	**159**	**117.3**	**83.0**	**49.5**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct Emiss. g/kWh el	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338		682	865	**0.88**	104	**761**	**578**
- brown coal			403		849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	22	31	40	48	53	56
- brown coal				0.0	33	47	44	41	59	76
- natural gas				0.0	1	2	5	7	8	9
Total				**0.0**	**56**	**80**	**89**	**97**	**120**	**141**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	11.0	15.7	20.0	24.2	26.5	28.5
- brown coal				0.0	14.1	20.2	18.9	17.7	25.2	32.3
- natural gas				0.0	0.3	0.7	1.7	2.6	2.9	3.1
Total				**0.0**	**25.4**	**36.5**	**40.6**	**44.5**	**54.7**	**63.8**

Source: Authors' own design

Tab. 13-8 Key data of the scenario variant “Realistisch I – only Kohle”

Scenario variant:	REALISTISCH I - ONLY KOHLE						
CCS proportions new plants	CPS =	0.75	CHPP =	0.40			
CCS proportions retrofitting	CPS =	0.40	CHPP =	0.20			
	Capacity of power plants with CO2 capture ++) from 2021; total value					with 2007 renewables data	
Year	New up to 2020	New from 2020 2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**4.20**	**5.82**	**6.54**	**7.26**	**9.13**	**11.00**
-hard coal/other solid fuels	10.82	2.32	3.13	3.96	4.80	5.62	6.45
-brown coal	6.32	1.89	2.69	2.58	2.47	3.51	4.55
-natural gas/oil/other gases	3.14	0.00	0.00	0.00	0.00	0.00	0.00
-nuclear power	0.00						
Public CHPP	**5.46**	**0.57**	**1.01**	**1.55**	**2.09**	**2.70**	**3.31**
- CHPP brown coal	0.33	0.00	0.14	0.27	0.40	0.81	1.22
- CHPP (hard coal, waste)	4.49	0.57	0.87	1.28	1.69	1.89	2.09
- CHPP (natural gas + oil)	0.64	0.00	0.00	0.00	0.00	0.00	0.00
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**0.57**	**1.33**	**1.90**	**2.47**	**2.84**	**3.21**
- CHPP (hard coal)	1.40	0.43	0.87	1.18	1.49	1.75	2.02
- CHPP (natural gas, oil)	0.51	0.14	0.46	0.72	0.98	1.08	1.18
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**5.21**	**7.70**	**9.27**	**10.84**	**13.59**	**16.33**
- hard coal/other solid fuels	16.71	3.32	4.88	6.42	7.97	9.27	10.57
- brown coal	6.65	1.89	2.83	2.85	2.87	4.32	5.77
- natural gas/oil/other gases	5.69	0.00	0.00	0.00	0.00	0.00	0.00
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**1.15**	**2.34**	**3.45**	**4.56**	**5.54**	**6.52**
CHPP brown coal	0.33	0.00	0.14	0.27	0.40	0.81	1.22
CHPP hard coal	5.89	1.00	1.74	2.46	3.18	3.65	4.12
CHPP natural gas	1.15	0.14	0.46	0.72	0.98	1.08	1.18
Additional capacity required for CCS (prop. additional requirement of fuel)		**1.29**	**1.91**	**2.24**	**2.57**	**3.30**	**4.03**
- hard coal/other solid fuels		0.69	1.01	1.33	1.65	1.92	2.19
- brown coal		0.60	0.90	0.91	0.92	1.38	1.84
- natural gas/oil/other gases		0.00	0.00	0.00	0.00	0.00	0.00

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**25.4**	**35.1**	**37.4**	**39.5**	**47.9**	**55.3**
- hard coal/other solid fuels	0	11.8	16.0	19.8	23.5	25.6	27.1
- brown coal	0	13.6	19.1	17.5	16.1	22.3	28.2
- natural gas/oil/other gases	0	0.0	0.0	0.0	0.0	0.0	0.0
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**1.5**	**2.7**	**4.1**	**5.5**	**6.8**	**8.1**
- hard coal/other solid fuels	0	1.5	2.3	3.3	4.4	4.7	5.0
- brown coal	0	0.0	0.4	0.7	1.1	2.1	3.0
- natural gas/oil/other gases	0	0.0	0.0	0.0	0.0	0.0	0.0
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**1.6**	**3.7**	**5.2**	**6.6**	**7.6**	**8.6**
- hard coal/other solid fuels	0	1.2	2.4	3.1	3.9	4.6	5.3
- natural gas/oil/other gases	0	0.4	1.4	2.1	2.8	3.0	3.3
Total power generation, TWh/a	**0.0**	**28.5**	**41.4**	**46.6**	**51.6**	**62.3**	**72.0**
- hard coal/other solid fuels	0	14.5	20.6	26.3	31.8	34.9	37.4
- brown coal	0	13.6	19.5	18.3	17.1	24.4	31.2
- natural gas/oil/other gases	0	0.4	1.4	2.1	2.8	3.0	3.3
Moderate utilisation, h/a		5478	5380	5030	4763	4586	4406
Proportion of total power generation; %		4.8	6.9	7.7	8.5	9.9	11.3

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	8.4	11.9	15.2	18.4	20.2	21.6
- brown coal	0.0	0.0	0.0	0.0	9.6	13.8	12.9	12.1	17.3	22.1
- natural gas	0.0	0.0	0.0	0.0	0.1	0.4	0.6	0.8	0.9	1.0
Total	**0.0**	**0.0**	**0.0**	**0.0**	**18.1**	**26.1**	**28.7**	**31.3**	**38.3**	**44.7**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**251**	**200**	**159**	**118.5**	**84.4**	**50.9**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338	Emiss.	682	865	**0.88**	104	**761**	**578**
- brown coal			403	g/kWh el	849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	22	31	40	48	53	56
- brown coal				0.0	33	47	44	41	59	76
- natural gas				0.0	0	1	2	3	3	4
Total				**0.0**	**55**	**80**	**86**	**92**	**115**	**136**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	11.0	15.7	20.0	24.2	26.5	28.5
- brown coal				0.0	14.1	20.2	18.9	17.7	25.2	32.3
- natural gas				0.0	0.2	0.5	0.8	1.0	1.1	1.2
Total				**0.0**	**25.3**	**36.3**	**39.7**	**42.9**	**52.9**	**62.0**

Source: Authors' own design

Tab. 13-9 Key data of the scenario variant “Realistisch II”

Scenario variant:	REALISTISCH II						
CCS proportions new plants	CPS =	0.50	CHPP =	0.30			
CCS proportions retrofitting	CPS =	0.30	CHPP =	0.15			
	Capacity of power plants with CO2 capture ++) from 2021; total value					with 2007 renewables data	
Year	New up to 2020	New from 2020 2025	2030	2035 *)	2040 *)	2045 *)	2050 **)
Condensation power stations	**20.27**	**2.80**	**3.88**	**4.79**	**5.69**	**7.10**	**8.51**
-hard coal/other solid fuels	10.82	1.54	2.09	2.74	3.39	3.96	4.54
-brown coal	6.32	1.26	1.79	1.77	1.74	2.39	3.03
-natural gas/oil/other gases	3.14	0.00	0.00	0.28	0.56	0.75	0.94
-nuclear power	0.00						
Public CHPP	**5.46**	**0.54**	**0.87**	**1.44**	**2.01**	**2.48**	**2.95**
- CHPP brown coal	0.33	0.00	0.11	0.20	0.30	0.61	0.91
- CHPP (hard coal, waste)	4.49	0.43	0.65	0.96	1.27	1.42	1.57
- CHPP (natural gas + oil)	0.64	0.11	0.11	0.27	0.44	0.46	0.47
Local heat + properties	**2.98**						
- BHPP (gas; oil)	0.66						
- BHPP (biomass)	2.32						
Industrial CHP	**5.56**	**0.43**	**1.00**	**1.42**	**1.85**	**2.13**	**2.41**
- CHPP (hard coal)	1.40	0.32	0.65	0.88	1.11	1.32	1.52
- CHPP (natural gas, oil)	0.51	0.11	0.34	0.54	0.74	0.81	0.89
- BHPP (natural gas, oil)	0.74						
- BHPP (biomass)	2.91						
Regenerative (excl. biomass)	**52.99**						
- run-of-river (+ supply to storage)	1.61						
- wind (20 a)	33.45						
- photovoltaics (30a)	16.92						
- geothermal energy	0.28						
- Import solar thermal	0.73						
- Import other regenerative energy	0.00						
Total new CCS power plants from 2021:	**87.26**	**3.77**	**5.74**	**7.65**	**9.56**	**11.71**	**13.87**
- hard coal/other solid fuels	16.71	2.30	3.40	4.58	5.77	6.70	7.63
- brown coal	6.65	1.26	1.90	1.97	2.04	2.99	3.94
- natural gas/oil/other gases	5.69	0.22	0.45	1.10	1.74	2.02	2.30
- total fossil fuels	29.05						
- nuclear	0.00						
- regenerative	58.21						
of which CHPP with CCS (from 2021)	**7.37**	**0.97**	**1.86**	**2.86**	**3.86**	**4.61**	**5.36**
CHPP brown coal	0.33	0.00	0.11	0.20	0.30	0.61	0.91
CHPP hard coal	5.89	0.75	1.31	1.84	2.38	2.73	3.09
CHPP natural gas	1.15	0.22	0.45	0.81	1.18	1.27	1.36
Additional capacity required for CCS (prop. additional requirement of fuel)		**0.92**	**1.39**	**1.77**	**2.16**	**2.70**	**3.25**
- hard coal/other solid fuels		0.48	0.70	0.95	1.20	1.39	1.58
- brown coal		0.40	0.61	0.63	0.65	0.96	1.26
- natural gas/oil/other gases		0.04	0.08	0.19	0.31	0.36	0.41

++) without additional capacity due to efficiency loss with CCS
*) including retrofitting of non-CCS plants built between 2011 and 2020 between 2031 and 2050
**) including 2nd generation new plants (replacement of plants built up to 2010) in 2050

Utilisable power generation using CCS power plants

	2020	2025	2030	2035	2040	2045	2050
Full load hours CPS, h/a							
- hard coal/other solid fuels	5250	5100	5100	5000	4900	4550	4200
- brown coal	7300	7200	7100	6800	6500	6350	6200
- natural gas/oil/other gases	3600	3500	3200	3100	3000	2500	2000
Power generation CPS; TWh/a	**0.0**	**16.9**	**23.4**	**26.6**	**29.6**	**35.1**	**39.8**
- hard coal/other solid fuels	0	7.9	10.7	13.7	16.6	18.0	19.1
- brown coal	0	9.1	12.7	12.0	11.3	15.2	18.8
- natural gas/oil/other gases	0	0.0	0.0	0.9	1.7	1.9	1.9
Full load hours public CHP, h/a							
- hard coal/other solid fuels	2600	2600	2600	2600	2600	2505	2410
- brown coal	2800	2800	2800	2750	2700	2600	2500
- natural gas/oil/other gases	3350	3500	3500	3500	3500	3500	3500
Power generation, public CHP; TWh/a		**1.5**	**2.4**	**4.0**	**5.7**	**6.7**	**7.7**
- hard coal/other solid fuels	0	1.1	1.7	2.5	3.3	3.6	3.8
- brown coal	0	0.0	0.3	0.6	0.8	1.6	2.3
- natural gas/oil/other gases	0	0.4	0.4	1.0	1.5	1.6	1.7
Full load hours, industrial CHP, h/a							
- hard coal/other solid fuels	3000	2800	2700	2650	2600	2600	2600
- natural gas/oil/other gases	2900	3000	3000	2900	2800	2800	2800
Full load hours, industrial CPS; TWh/a		**1.2**	**2.8**	**3.9**	**5.0**	**5.7**	**6.4**
- hard coal/other solid fuels	0	0.9	1.8	2.3	2.9	3.4	3.9
- natural gas/oil/other gases	0	0.3	1.0	1.6	2.1	2.3	2.5
Total power generation, TWh/a	**0.0**	**19.7**	**28.5**	**34.5**	**40.2**	**47.5**	**53.9**
- hard coal/other solid fuels	0	9.9	14.1	18.5	22.8	25.0	26.8
- brown coal	0	9.1	13.0	12.6	12.1	16.7	21.1
- natural gas/oil/other gases	0	0.7	1.4	3.4	5.3	5.8	6.0
Moderate utilisation, h/a		5212	4969	4511	4210	4055	3885
Proportion of total power generation; %		3.3	4.8	5.7	6.6	7.5	8.5

CO_2 capture: emission reduction (million t/a) and additional requirements of fuel (PJ/a)

Scenario 2008 - D (coal + CCS)	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Additional emission reduction										
- hard coal/other solid fuels	0.0	0.0	0.0	0.0	5.7	8.2	10.7	13.2	14.5	15.5
- brown coal	0.0	0.0	0.0	0.0	6.4	9.2	8.9	8.6	11.8	14.9
- natural gas	0.0	0.0	0.0	0.0	0.2	0.4	1.0	1.5	1.7	1.7
Total	**0.0**	**0.0**	**0.0**	**0.0**	**12.3**	**17.8**	**20.6**	**23.3**	**28.0**	**32.1**
CO2 emissions without CCS	**309**	**305**	**296**	**296**	**269**	**226**	**188**	**150**	**123**	**95.6**
CO2 emissions with CCS	**309**	**305**	**296**	**296**	**257**	**209**	**168**	**126.5**	**94.7**	**63.4**
Reduction factors (g/kWhel) compared to reference power station			Fuel g/kWh th	Only direct Emiss. g/kWh el	Without CCS	Produced with CCS	Degree captured	Emitted with CCS	To be captured	Reduction
- hard coal			338		682	865	**0.88**	104	**761**	**578**
- brown coal			403		849	1176	**0.88**	141	**1035**	**708**
- natural gas			202		337	417	**0.88**	50	**367**	**287**
Additional requirements of primary energy										
- hard coal/other solid fuels				0.0	15	21	28	34	38	40
- brown coal				0.0	22	32	30	29	41	51
- natural gas				0.0	1	1	4	6	6	6
Total				**0.0**	**38**	**54**	**62**	**69**	**84**	**98**
Additional requirements compared to reference power station			Eta without CCS	Eta with CCS	Fuel requirements PJ th/PJ el REF	CCS			Additional requirements absolute	relative
- hard coal			**0.495**	**0.410**	2.020	2.439			**0.4188**	**1.207**
- brown coal			**0.475**	**0.360**	2.105	2.778			**0.6725**	**1.319**
- natural gas			**0.600**	**0.510**	1.667	1.961			**0.2941**	**1.176**
CO_2 capture rate										
- hard coal/other solid fuels				0.0	7.5	10.7	14.1	17.3	19.0	20.4
- brown coal				0.0	9.4	13.5	13.0	12.5	17.3	21.8
- natural gas				0.0	0.3	0.5	1.2	1.9	2.1	2.2
Total				**0.0**	**17.2**	**24.7**	**28.4**	**31.8**	**38.5**	**44.4**

Source: Authors' own design

13.3 Appendix 3: Pipeline infrastructure scenarios

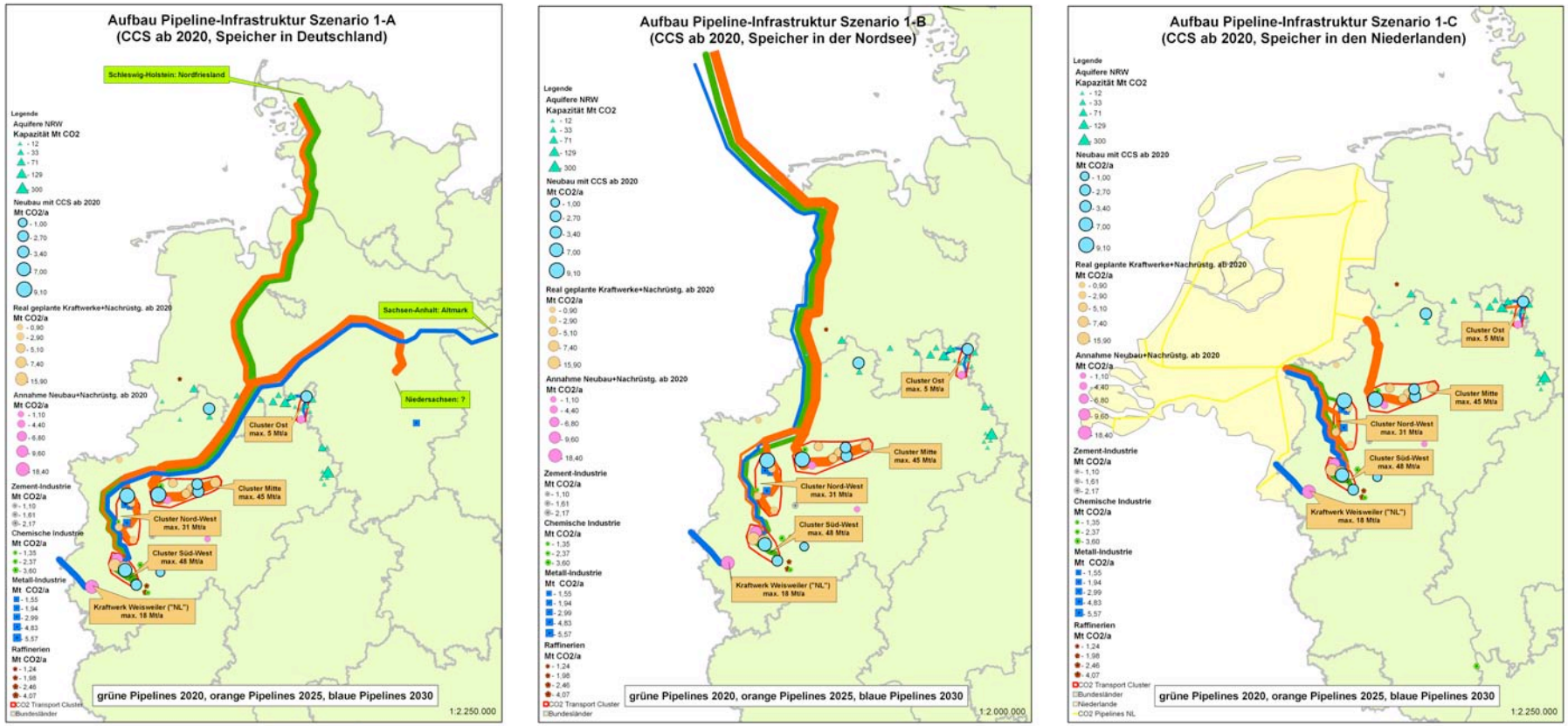

Fig. 13-1 Exemplary illustration of pipeline infrastructure scenarios resulting from a CCS-MAX strategy in North Rhine-Westphalia (total distances of 4,330 km in scenario 1-A, 8,380 km in scenario 1-B and 1,140 km in scenario 1-C)

Source: WI 2009