Since the beginning of industrialisation, the fossil energy sources that have been created over millions of years have been burnt in an ever-increasing amount and largely used for electricity, heat and mobility. The carbon dioxide (CO₂) released in the process is accumulating increasingly in the Earth’s atmosphere, reinforcing the greenhouse effect there and thus leading to global warming. The consequence is a reinforcement of the naturally occurring climate change. Only a rapid and considerable reduction in global CO₂ emissions can still limit the consequences of climate change. The energy sector is one of the central starting points for this. Alongside saving energy through more efficient technologies and the use of renewable energy technologies, it is also necessary to develop and implement low carbon technologies industrially.

The key areas are more efficient power plants and the capture and geological storage of CO₂ – Carbon Capture Storage (CCS). The future aim of CCS technologies is to capture the CO₂ released during combustion processes with as little extra energy requirement and cost as possible, transport it to the gas storage reservoir and then store it securely over the long term. Research and development work is being carried out for each of these three process stages, some of the goals being to improve the energy and environmental balance of all the stages, to ascertain the chemical processes taking place in the filled reservoir as well as optimising the safety and long-term stability of the reservoir. In terms of technology, working with CO₂ is not new territory. The gas has been used for years in crude oil and natural gas production to stimulate deposits, and naturally occurring CO₂ is captured and stored during natural gas production.

The German Federal Government is supporting research and development into low-carbon power plant technologies. The “COORETEC” concept (CO₂ reduction technologies) of the Federal Ministry of Economics and Technology is concentrating on the separation and transportation of CO₂ in addition to increasing power plant efficiency. Research projects into storing CO₂ are being funded by the geotechnology programme of the German Federal Ministry of Education and Research. In addition to this, Germany is involved in international projects organised by the EU and the International Energy Agency (IEA).
Carbon Capture Storage (CCS) technologies will first be tried out on new power plants. As soon as the technology as a whole is proven to be technically, economically and environmentally feasible, existing power plants which already have modern technology (capture ready plants) are to be upgraded also. In order for CCS technologies to be able to make the breakthrough on a large scale, each of the three sub-processes (separation, transport and storage) must be optimised. Current estimates assume that capture will account for 60%, compression 15%, transport 10% and storage 15% of the additional costs.

The aim is to make it possible to spatially and technically integrate the capturing methods in the power plants and their processes. For economic and technical reasons, the CO₂ gas must be liquefied and due to the geographic conditions in Germany the best way to then convey it to the storage sites is pipelines. Under these circumstances, when deciding where to site a power plant, the physical proximity to the CO₂ reservoirs and therefore a reduction in transport expenditure will play a role in the future.

In Germany, only deep geological formations with adequate cap rock are taken into consideration as storage sites. The gas is to permanently remain there without affecting current or future drinking water resources. Such stores are to have a maximum leakage rate of 0.01% per year, i.e. after 1,000 years 90% and after 10,000 years 40% of the CO₂ would still be in the store. That is almost the same as the cycle of natural warm and cold periods.

The chemical purity of the CO₂ is also of importance. Undesirable impurities, such as water vapour or sulphur compounds increase the amount of energy needed during gas compression. Furthermore, they can cause corrosion of all the metal components as well as unwanted chemical reactions with the sealing devices of the wells and the rock layers surrounding the store.

Methods for capturing CO₂ in the power plant

Sulphur dioxide and other gases can be successfully removed from the flue gas in power plants. It is also possible to capture CO₂ although a considerably greater amount has to be disposed of compared to other gases. There are currently three methods of capturing CO₂ from the power plant process (Fig. 3) which are considered promising. The CO₂ can either be captured before or after the combustion process or accumulated in concentrations of over 90% by combustion in a very oxygen-rich atmosphere (oxyfuel). The processes vary according to their energy requirement, chemical purity and the achievable capture rates of the CO₂, the space required as well as the use of solvents and the possibility of upgrading existing power plants.

Post-Combustion (CO₂ capture after combustion)

With this method, CO₂ is captured after combustion by means of a chemical flue gas scrubbing. The exhaust gas – under low partial pressures – is brought into contact with a solvent (e.g. an alkaline solution) in an absorption unit and dissolves in the liquid. The following thermal desorption processes capture and take away CO₂. The solvent can then be used once again. This method has, until now, been developed to the furthest extent and is opening up the prospect of upgrading the more modern power plants that currently exist. It is, however, comparatively energy- and cost-intensive.

Oxyfuel

With this method, the nitrogen is already captured from the air before combustion and just the remaining air, which contains almost exclusively oxygen, is used. This reduces the exhaust gas amount by approx. 75% and this gas consists of approx. 70% CO₂. The remainder is water vapour which is condensed out. At the end of the process, the CO₂ is available in a highly concentrated form. During combustion with a very high percentage of oxygen, the temperatures must not be so high that they may damage the materials. Until now, air separation has been carried out by means of refrigeration technology (“freezing out” the nitrogen) which is involves high costs in terms of energy and plant facilities needed. Researchers are working on energy-saving separation processes using membranes. Further research and development work is still necessary for the oxyfuel process. Individual test systems are already in operation in power plants.

Pre-Combustion (Capture before combustion – Combined power plant)

This method too only uses the oxygen captured beforehand from the air. Before combustion, coal is converted into a synthesis gas which consists predominantly of hydrogen and carbon monoxide (CO). By adding water vapour, the CO is converted to CO₂ and further hydrogen is generated. The resulting hydrogen-rich synthesis gas is...
burnt and used in a combined gas and steam turbine power plant process.

CO₂ capture is performed with a gas scrubbing process. The advantage of this method is that such power plants can reach an efficiency of over 40% – even with an almost complete CO₂ capture – and are also able to produce synthetic fuels and chemical elements.

Medium-term research objectives are economic optimisation of the process, adapting the gas turbine to the hydrogen-rich combustion gas as well as optimising the gasification process and CO₂ capture. In Germany, the first IGCC power plant will be completed in 2014.

The aim of geological storage is to keep CO₂ emissions away from the biosphere for a long period of time. Natural gas deposits stored over millions of years show that gases can be geologically enclosed. Only depleted natural gas deposits and rock layers with adequate cap rock that contain salt water and exceed a depth of 800 m will be considered as storage reservoirs for CO₂ in Germany. In Germany, three quarters of the suitable geological formations can be found in Northern Germany. This fact is known because of previous exploratory drilling for crude oil and natural gas. There are geological formations below the North Sea from which natural gas is currently being extracted. They are not yet included in the estimated values in Fig. 5 and represent additional and extensive storage capacities.

At the storage location, the liquid CO₂ is injected to a depth of about 1,000 m (Fig. 6).

Because of the hydrostatic pressure, it is 500-times denser here than as a gas at the Earth’s surface and therefore makes full use of the storage volume. Storage occurs either physically (CO₂ is prevented from escaping by pressure and cap rock) or chemically (new mineral formation). During injection, the pressure and temperature must be adapted to the specific geological and hydrological conditions of the storage facility.

Continuous monitoring ensures that the CO₂ spreads out underground and that the sealing is permanent. The research subjects are: Investigation into CO₂ purity, long-term behaviour, the geochemical and geophysical processes in the depths, drinking water protection (e.g. by displacing salt water) as well as storage management, safety concepts and material development (well cement, corrosion protection).

The future amount of CO₂ depends on many factors. Electricity production in Germany will be changing due to more efficient power plants, changes in the energy mix and energy prices. Forecasts predict that, by 2030, power plants will generate about 60 million tonnes of CO₂ that can be stored. For transport in pipelines, the gas will be compressed and liquefied using compressors, which will consume additional energy. The transport costs will be comparable to oil and gas pipelines.

Currently there are approx. 3,100 km of CO₂ pipelines worldwide used in connection with crude oil and natural gas production. To implement CCS a CO₂ pipeline network is indispensable. This network still has to be built up in Germany. The State is to provide specifications in planning law so that the routes can be planned and the storage locations set aside. The pipeline network is to be built up and run by the power plant operators according to this legal framework.

### Transporting the CO₂ to the storage facility

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### Geological storage of the CO₂

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<table>
<thead>
<tr>
<th>Deposit</th>
<th>Capacity [Billions t CO₂]</th>
<th>Static range relating to total power plant emissions 2002 [%]</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Depleted gas fields</td>
<td>690</td>
<td>65</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Depleted oil fields</td>
<td>120</td>
<td>11</td>
<td>0,1</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Deep saline aquifers</td>
<td>400 – 10,000</td>
<td>38 – 940</td>
<td>12 – 28</td>
<td>34 – 78</td>
</tr>
<tr>
<td>Non-exploitable coal seams</td>
<td>40</td>
<td>4</td>
<td>0,4 – 1,7</td>
<td>&lt; 2</td>
</tr>
</tbody>
</table>

Sources: * = IPCC (2002); ** = BGR (2004)
„COORETEC Lighthouse” concept

COORETEC bundles the research and development activities of energy policy, research and of the energy industry for low-emission power plants with fossil energy sources and CCS technologies. These are to be generally available on the market by the year 2020. The first power plant concepts and components, such as oxyfuel combustion, an IGCC power plant and a combined gas and steam turbine power plant with more than 60% efficiency, are in the trial or planning stages.

COORETEC has the following technical objectives for the field of CCS technologies:
- lowering the cost of CO₂ capture and storage from currently between €50 and €70 to less than €20 per ton CO₂ in the future,
- reducing efficiency loss due to CO₂ capture and storage from between 9% and 13% today to 6%–11%,
- a high level of reliability and flexibility in order to be able to react quickly and efficiently to volatile electricity and energy markets and
- extending gasification technologies (providing synthetic fuels and elements to the chemical industry).

### Conclusion and perspectives

Far-reaching resolutions regarding energy policy and climate protection were passed in 2007. All EU countries are endeavouring to reduce greenhouse gas emissions by at least 20% by 2020 (30% if other industrial nations also participate). Since the energy requirement of the newly industrialised countries will rise in the long term, the CO₂ emissions of the industrial nations will have to be lowered by even 60% – 80% by 2030.

To reach these targets, renewable energy sources are to contribute 20% (current figure: 6.5%) to the total energy consumption in Europe by 2020. Energy productivity is to rise by 20% Europe-wide. For Germany, this means an annual increase in efficiency of approx. 3%. These target values are ambitious and call for a lot of effort. As far as the above CO₂ reduction targets are concerned, these measures alone will not suffice; instead, highly efficient fossil power plants and carbon capture and storage technologies will be necessary in the foreseeable future. The climate protection goals can only be reached by using all the options. The global energy need, which will continue to grow rapidly, must also be taken into consideration. It is expected that world electricity consumption will double by the year 2030.

Carbon capture and storage technologies must still undergo considerable research and development if they are going to be available to the market on a large scale from 2020. They can also be used in refineries as well as cement and steel works. Fundamental research in the technology and potential of geological storage as well as investigation in its long-term stability and environmental impact have begun. Results are expected from the evaluation of the surveys being carried out in the European storage research project CO₂SINK in Ketzin (Fig. 1), and a larger project, currently in the planning stage, in a former natural gas deposit.

Other countries such as Australia, Japan and the USA are also working on the development and market introduction of CCS technologies. The International Energy Agency and the European Union are conducting international cooperation projects. In the coming years, up to 12 demonstration power plants with CO₂ capture are planned within the EU.

### ADDITIONAL INFORMATION

- Further information about the COORETEC support initiative can be found at www.cooretec.de

### Literature
- A list of links about the subject can be found under www.bine.info “Service/InfoPlus”
- “Entwicklungsstand und Perspektiven von CCS-Technologien in Deutschland”. Joint report of the BMWi, BMU and BMBF for the German Federal Government dated 19th Sept. 2007. Available at: www.bmw.de

### Images
- Fig. 1: Geoforschungszentrum Potsdam, Project CO₂SINK
- Fig. 2: Deutsches Vulkan Museum, Mendig
- Fig. 3: Technische Universität Hamburg, Harburg. From: Project info 6/2007 “Kraftwerke mit Kohlenverbrennung”
- Fig. 4: Research Centre Jülich, STE working report 1/2006
- Fig. 5: Lighthouse COORETEC concept

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