



CO₂ SCRUBBING

Ultra-modern climate protection for coal-fired power plants



RWE POWER – ALL THE POWER

RWE Power is Germany's biggest power producer and a leading player in the extraction of energy raw materials. Our core business consists of low-cost, environmentally sound, safe and reliable generation of electricity and heat as well as fossil fuel extraction.

In our business, we rely on a diversified primary energy mix of lignite and hard coal, nuclear power, gas and hydropower to produce electricity in the base, intermediate and peak load ranges.

RWE Power operates in a market characterized by fierce competition. Our aim is to remain a leading national power producer and expand our international position, making a crucial contribution toward shaping future energy supplies.

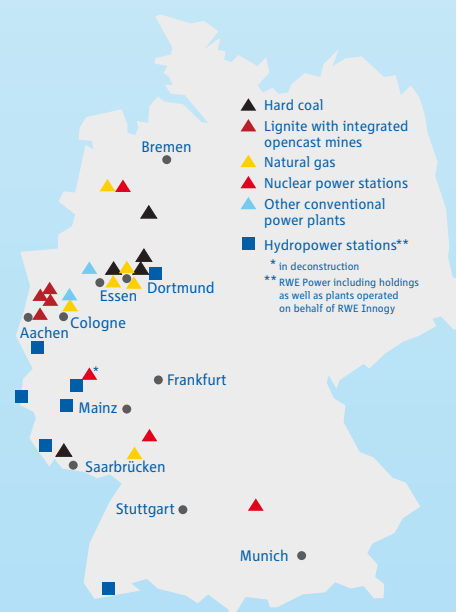
A strategy with this focus, underpinned by efficient cost management, is essential for our success. All the same, we never lose sight of one important aspect of our corporate philosophy: environmental protection. At RWE Power, the responsible use of nature and its resources is more than mere lip service.

Our healthy financial base, plus the competent and committed support of some 17,500 employees under the umbrella of RWE Power, enable us to systematically exploit the opportunities offered by a liberalized energy market.

In this respect, our business activities are embedded in a corporate culture that is marked by team spirit and by internal and external transparency.

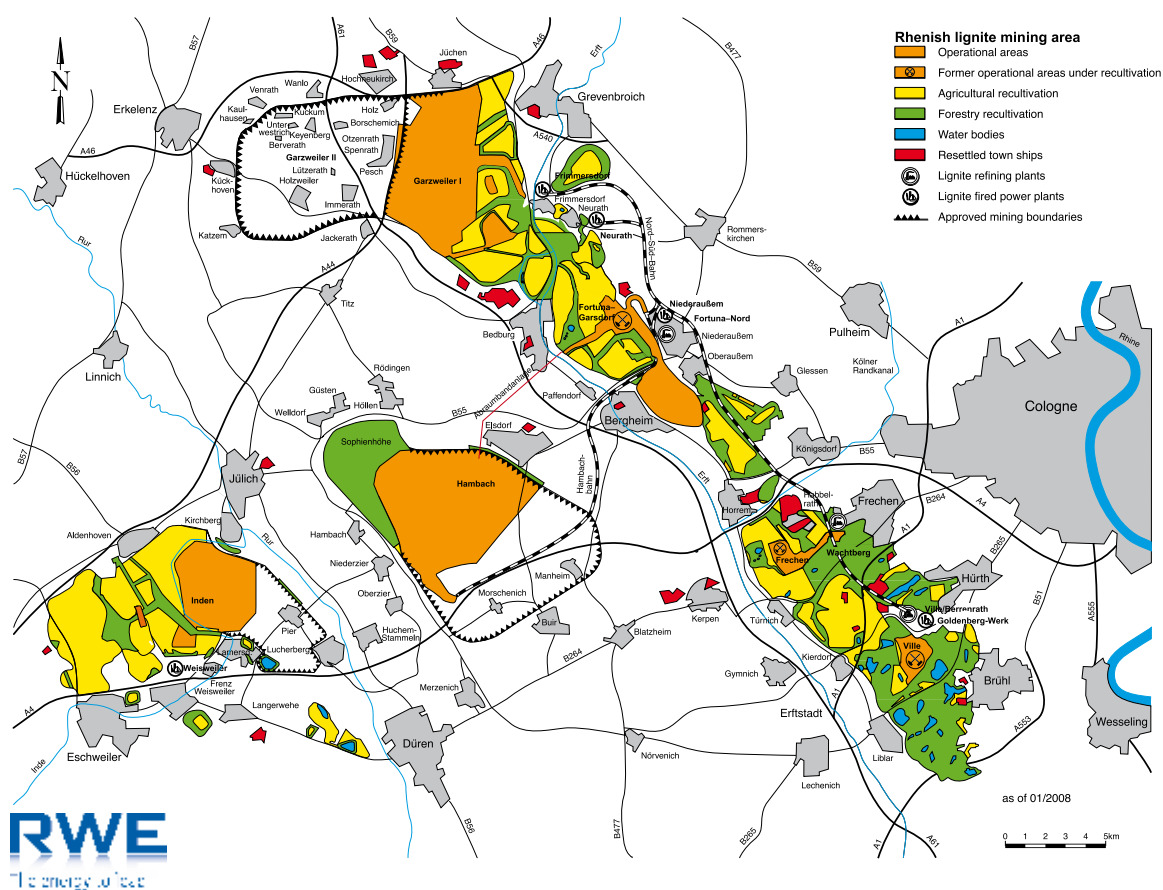
With an about 30 percent share in electricity generation, we are no. 1 in Germany, and no. 3 in Europe, with a nine percent share. We wish to retain this position in future as well. That is what we are working for – with all our power.

One of the focuses of RWE Power is on the Rhenish lignite-mining area where the Company mines some 100 million tons of lignite every year, most of which is used to generate electricity. Lignite needs no subsidies, offers work and training to many people in the mining area, underpins spending power with the salaries and taxes the Company pays, so that it is an economic asset for the entire region.



LIGNITE – BACKBONE OF GERMANY’S ELECTRICITY SUPPLY

Lignite is Germany’s most important domestic energy source. It can be mined without state subsidies and is found in Lusatia, Central Germany and, with the biggest reserves, the Rhineland.



In the Rhenish mining area, some 100 million tons of this energy resource are extracted each year in the opencast mines Garzweiler, Hambach and Inden. Ninety million of this total is combusted in RWE’s power plants, which have a total gross capacity of some 11,000 MW, in order to generate an annual

70 billion kWh of electricity. This amount covers 15 percent of Germany’s electricity needs. The remaining ten million tons or so are processed in the Company’s upgrading facilities to make briquettes, pulverized lignite, fluidized-bed lignite and coke for the heating market and environmental protection.

CARBON DIOXIDE

When a fossil fuel is burned, carbon dioxide – CO₂ for short – is inevitably produced as well. This is as true of coal as it is of natural gas and mineral oil.

CO₂ is a natural component in the atmosphere. Humans and animals emit it every time they exhale. Carbon dioxide, just like water vapour, shares the responsibility for the natural greenhouse-gas effect and brings Earth its moderate temperatures. The CO₂ ensures that some of the solar radiation does not escape back into space immediately, but remains in the atmosphere to warm the Earth's surface. Plants and sea algae need CO₂ to survive: they absorb it and, as a waste product, return the oxygen on which humans and animals, in their turn, depend.

One thing is clear: CO₂ is indispensable for life on Earth. But that does not mean that humans can release as much as they like into the atmosphere. So, if we are not to unduly inflate the natural greenhouse-gas effect and the observed rise in global temperatures, it makes sense to curb man-made carbon dioxide emissions.

Besides industry, traffic and private households, we find that the energy sector, as operator of coal- and gas-fired power plants, accounts for a large share of CO₂ emissions. So it is especially duty-bound to lower its CO₂ emissions perceptibly.



EMITTING LESS CO₂

Lignite is one of the cornerstones of Germany's electricity supply. Yet, the operation of fossil-based power stations also happens to be associated with the release of carbon dioxide.

If you wish to reduce these emissions, there are two points of attack. On the one hand, you can avoid CO₂ emissions from the very outset. The higher the efficiency with which the chemical energy stored in coal is converted into electric energy, the less coal is needed to produce one kilowatt hour of electricity, and the less CO₂ is released. That is why RWE is gradually replacing older power plant units with new-builds. Their efficiency is over 43 percent for lignite and 46 percent for hard coal. Since 2003, the first lignite-fired power station with optimized plant engineering (BoA 1) has been delivering electricity at Niederaussem (Rhein-Erft county). Two further BoA units are currently being built at Neurath (Rhein county Neuss).



Niederaussem power plant with BoA unit and WTA in the foreground.

Another example of growing efficiency is the use of pre-dried raw lignite in future lignite-fired power stations. For this purpose, RWE Power has been developing its own drying technology since 1993: fluidized-bed drying with internal waste heat utilization (WTA). At the Niederaussem BoA unit and, hence, in RWE's Coal Innovation Centre, a WTA prototype system started work in 2009. Using this process, the efficiency of future lignite-based power plants can be raised to more than 47 percent.

At Hürth near Cologne, RWE is planning the world's first commercial-scale lignite-fired power station with integrated gasification and CO₂ capture. There, the lignite is not combusted, but first converted into a fuel gas. This gas is cleaned of CO₂ before being burned in a turbine. The separated CO₂ is compressed and flows through a pipeline into a storage facility below ground. The 450-MW power plant is to go on stream in 2015.

A completely different approach to lowering CO₂ is the downstream scrubbing of the flue gases of a conventional power station. This involves removing the greenhouse gas from the flue-gas stream – by so-called CO₂ scrubbing – after coal combustion and before the gas is released into the atmosphere.

WHY CO₂ SCRUBBING?

Imported fossil fuels are becoming scarcer and more expensive – because their geological deposits will be running out in the foreseeable future, and because they are used at times as instruments of power in economic and foreign policy. Germany's high dependence on imports for its energy supply makes it clear how sensible and necessary domestic lignite is for power generation.



Lignite-based power stations generate electricity reliably and at low cost. Their classic flue-gas components sulphur dioxide, nitrogen oxide and dust have long since stopped being a problem thanks to optimized combustion technology and cleaning systems. Using processes like CO₂ scrubbing, it could also be possible in future to avoid an additional 90% or so of CO₂ emissions in coal-fired power generation. This method, referred to by specialists as PCC (post-combustion capture), is downstream of a power plant's combustion process. So, the process starts with CO₂ capture before the flue gas – cleaned of dust, nitrogen oxides and sulphur dioxide – reaches

the atmosphere via a power station's cooling towers or stacks. The advantages of such a low-CO₂ power plant technology are obvious: the modern coal-fired power stations being built today can be retrofitted with such a CO₂-capture system, because it does not interfere with a power plant's actual combustion process. Even in a possible failure of the CO₂-scrubbing system, electricity can still go on being produced reliably, i.e. the availability of the power plant is guaranteed at all times. This being so, all new RWE coal-fired power stations are in principle being built "capture-ready", i.e. they can be retrofitted with CO₂-scrubbing systems.

HOW CO₂ SCRUBBING WORKS

At the core of a CO₂-scrubbing system is an absorber in which a scrubbing solution takes up the carbon dioxide from the power plant's flue gas at low temperatures.

The flue gas coming from the power station has a temperature of approx. 65°C after desulphurization. It first reaches a wet scrubber where it is cooled and freed from any residual traces of sulphur dioxide (SO₂) that might impair CO₂ scrubbing. A fan then transports the flue gas to the absorber, through which it flows bottom-up. This is where it meets the scrubbing solution, an aqueous solution of amines (a group of organic substances), which is added at the head of the absorber and, in a counter current flow, takes up the CO₂ from the flue gas. The low-CO₂ flue gas is scrubbed with water before leaving the absorber to remove any residues of the scrubbing agent, and finally reaches the atmosphere by the normal route via the stack or cooling tower.

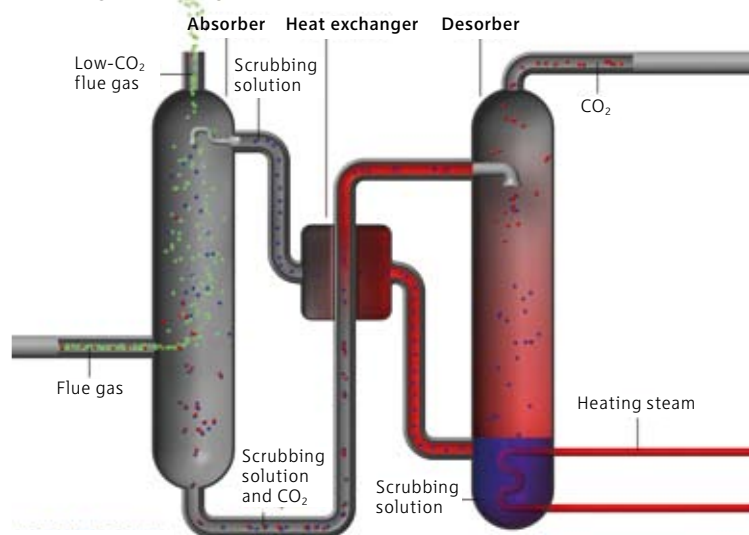
The scrubbing solution saturated with CO₂ is conducted to a so-called desorber and heated there to approx. 120°C, which strips the CO₂ from the liquid and makes it available in a high purity. The hot scrubbing agent freed from CO₂ is cooled and then pumped back to the absorber, where the scrubbing cycle can start again.

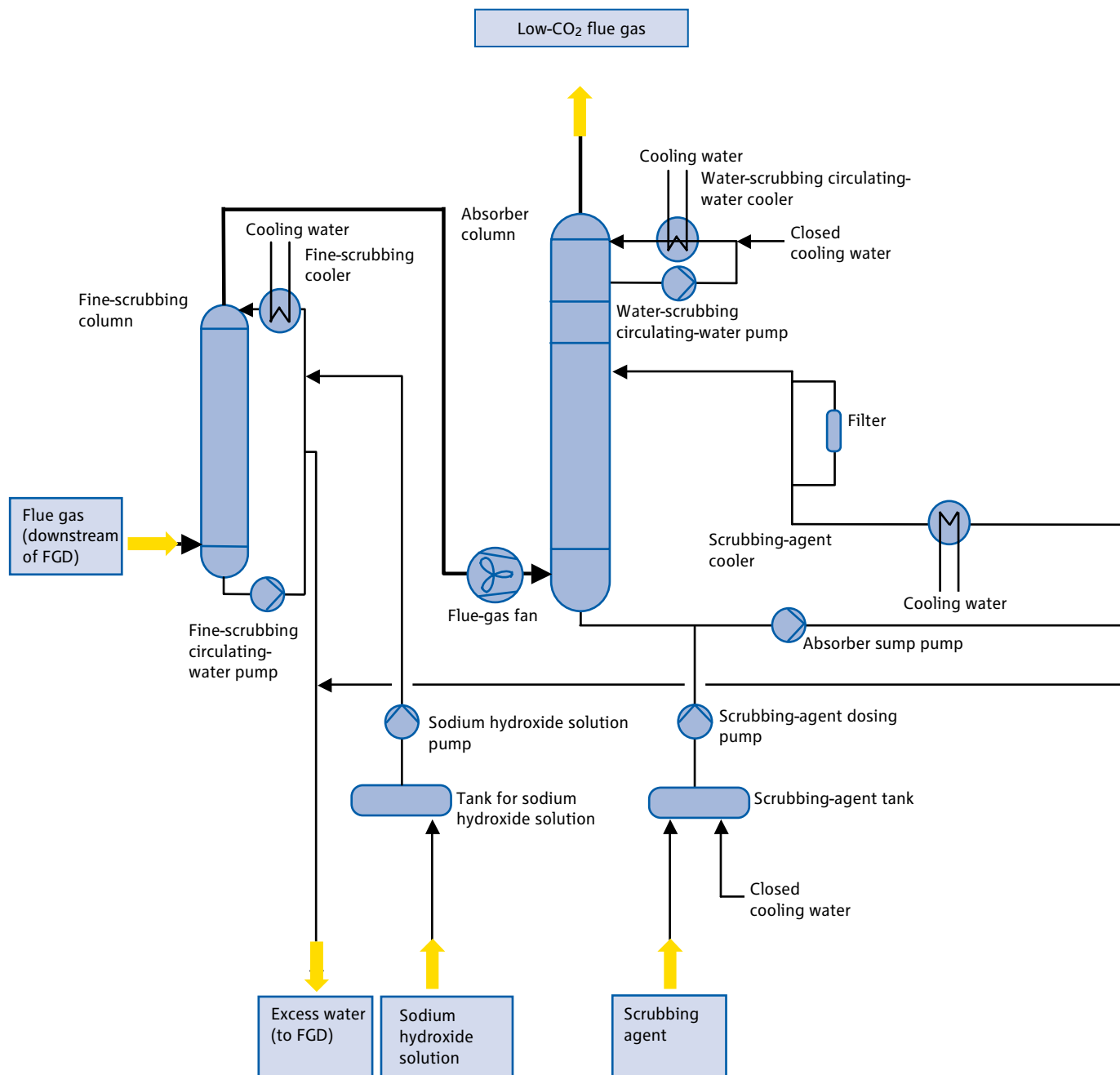
The captured CO₂ is to be compressed in future large-scale plants for transportation to the storage sites through pipelines for injection into suitable geological structures, like deep saline formations or depleted natural-gas reserves.

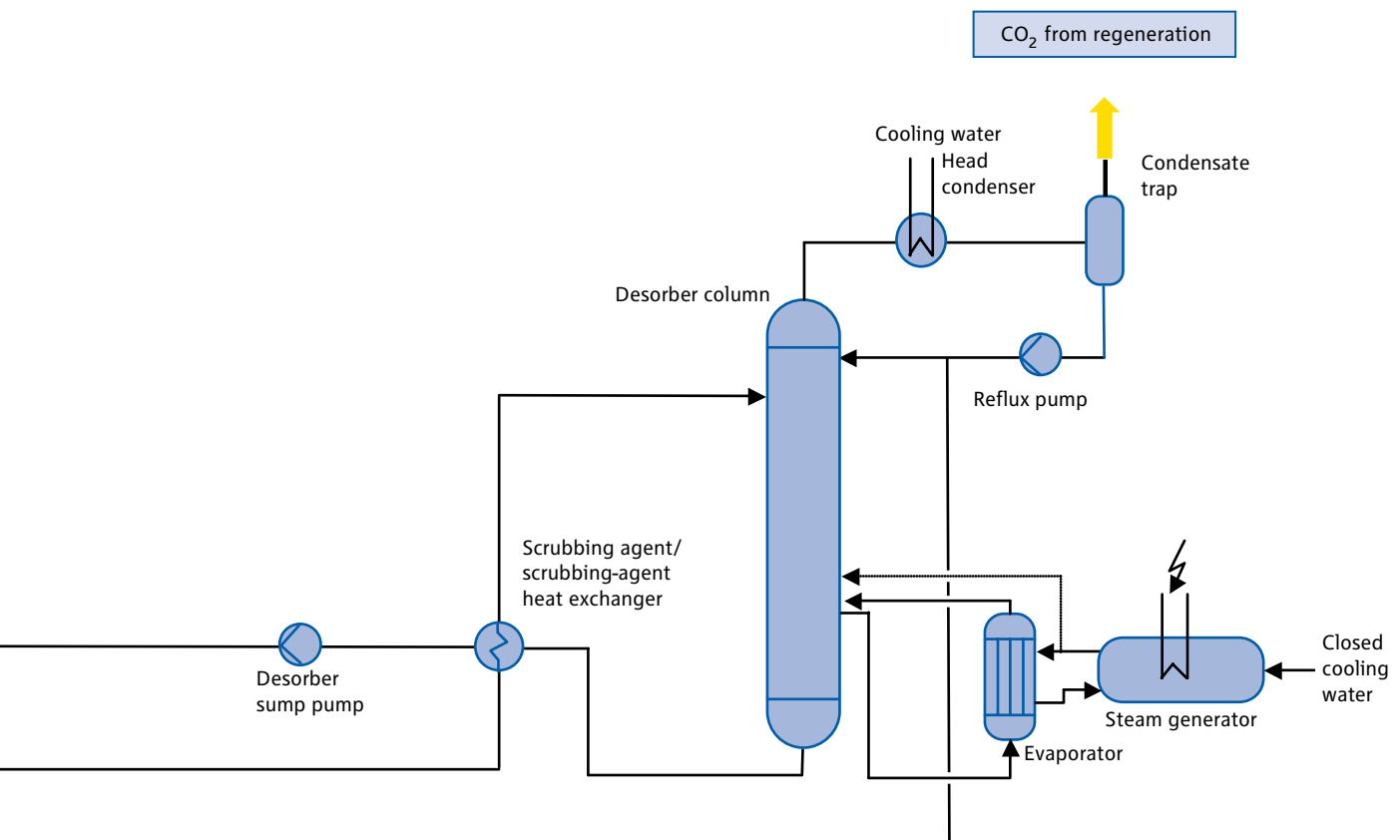
In the chemical industry, CO₂ scrubbing is a proven process used to separate carbon dioxide from natural gas, for example, for use in the beverage or fertilizer sector.

The application in CO₂ capture from flue gases is new, and the scrubbing technique must be adapted to the conditions of a power plant. For instance, the flue-gas streams of a coal-based power station contain three to five percent oxygen, while the gas streams usual in the chemical industry hold next to no oxygen. What is more, today's plant engineering for CO₂ scrubbing has higher energy needs than RWE is aiming at for deployment in power stations. This makes it necessary in a first step to trial the CO₂-scrubbing technique optimized for power-plant conditions in a pilot and to gain experience in new, improved scrubbing solutions that require less energy for CO₂ capture.

CO₂ flue-gas scrubbing



PROCESS DIAGRAM
OF THE PILOT PLANT



THE CO₂-SCRUBBING PILOT PLANT AT NIEDERAUSSEM

In the summer of 2009, the pilot CO₂-scrubbing plant at Niederaussem was commissioned as the first of its kind in Germany. For the first time, carbon dioxide is captured from the flue gas of a conventional power plant using the CO₂-scrubbing process.

Before modern coal-fired power plants can be equipped with CO₂-capture facilities on a large scale, it is necessary to trial the components and the process as a whole in a power station under the most realistic conditions possible. The Coal Innovation Centre at the BoA unit of the Niederaussem power plant is the trailblazer in modern lignite-based power generation and the ideal site for a CO₂-scrubbing pilot system. Since this is also where the test plant REAplus for the

highly efficient desulphurization of flue gases, too, is operated, it offers optimal conditions for trialling progressive power-plant engineering.

To adapt CO₂-scrubbing technology for application in power plants, RWE Power has entered into a partnership with the companies BASF and Linde, which are in the world's premiere league in their particular field. They can build up on long years of experience in CO₂ scrubbing. For the Niederaussem project, BASF has developed an improved scrubbing process on the basis of new scrubbing solvents. Linde has built the pilot plant on behalf of RWE Power.

There, all aspects of CO₂ scrubbing will be investigated under actual power plant conditions to check their functioning and gain experience for later commercial-scale systems. Being trialled here are not only new, energy-efficient scrubbing liquids to separate the carbon dioxide from the flue gas, but also energy-optimized process technology from BASF and improved plant engineering from Linde. The aim of the development program is to lower considerably the energy demand for capturing CO₂ compared with the processes that are customary today.

The pilot system has all the components of a commercial-scale unit, so that it can generate robust research results. 0.05 percent of the flue gas is





diverted from the BoA unit and scrubbed of CO₂. In this way, the pilot plant can capture approx. 300 kg carbon dioxide per hour, which – with the flue-gas quantity processed – is equivalent to 90 percent of the CO₂ being captured. The scrubbed CO₂ is fed back into the flue-gas stream of the BoA unit. This is because Niederaussem offers no suitable options at present for storing the carbon dioxide or finding other uses for it. In future, large-scale applications solutions will be available here.

The costs of the CO₂ project at Niederaussem amount to € nine million, to which the Federal Ministry of Economics and Labour is contributing 40 percent (promotion code 0327793 A-C). It confirms the importance of this development for future low-CO₂ power generation from fossil fuels.

BASF WITH MANY CONTRIBUTIONS TO CLIMATE PROTECTION



CO₂ can be “scrubbed out” of the flue gases of power plants – BASF is developing scrubbing agents and technology.

Energy savings, increases in efficiency and technological availability are the fundamental aims of the cooperation with RWE Power and Linde, to which BASF attaches great importance. In this setting, BASF is committed to developing carbon dioxide capture and storage (CCS) toward a commercially available technology in the coming years.

BASF brings into the cooperation its comprehensive expertise in separating CO₂ from gases, so-called gas scrubbing. Under the trade name aMDEA®, BASF is marketing a “package” of “gas scrubbing agents” along with the appropriate technology. This package has been proving its worth for many years now in more than 200 plants worldwide, e.g. in cleaning synthesis gas and natural gas. The process for scrubbing CO₂ out of power plants’ flue gases will be a further development of this tried-and-tested technology.

The crucial factors for the development of a suitable gas-scrubbing process are the “CO₂-scrubbing agents” in the process, i.e. the chemicals that “scrub out” the CO₂ and their properties in terms of energy efficiency and oxygen stability. A suitable scrubbing agent must have very specific physico-chemical properties. These include suitable vapour pressure and viscosity, and the scrubbing agent must not be toxic. If a CO₂-scrubbing agent meets these basic requirements, other properties come to the fore, namely the ability to absorb a certain amount of CO₂ as quickly as possible. As a general rule: the more and the faster, the better. Once such criteria, too, are met, the issue of stability must be clarified. The oxygen contained in the flue gas may mean that the scrubbing agent no longer works. Only scrubbing agents that are sufficiently stable against oxygen will carry the day.

It all started with the pre-selection of suitable products from BASF’s extensive portfolio of some 400 substances. After an elaborate selection process, about 150 “candidates” were left, and these were subjected to a comprehensive shortlisting procedure. At the end of this process step there will be ten to twenty potentially suitable “gas scrubbing agents”, and these will be tested at BASF’s Verbund site Ludwigshafen in a model unit, a so-called “mini plant”, to check their fitness for purpose in practice. The substances rated as positive here qualify for subsequent testing in RWE’s pilot plant at Niederaussem.



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BASF and climate protection

BASF is engaged in climate protection worldwide. Using products, technologies and system solutions from BASF, customers and end consumers today are already saving three times more greenhouse-gas emissions in many areas of life than are emitted in the production and disposal of all BASF products. In total, more than 250 million tons of CO₂ can be saved worldwide thanks to BASF products – be it in housing construction, in the automotive sector, or in industrial production. For its comprehensive carbon balance, BASF received the European Responsible Care Award from the European chemical association CEFIC in October 2008.

THE LINDE GROUP



In the above partnership Linde, as the engineering company, has the responsibility to design and build the plant with the specific requirement to meet the requirements of a power station.

The Linde Group, a world-leading gas and engineering company, is represented in some 100 countries and employs more than 50,000 people worldwide. Its engineering division is internationally recognized as a leader in the field and focuses on complex high-tech systems (e.g. in natural gas liquefaction, air separation and plants for hydrogen, synthesis gas and olefin production). Linde's know-how in the development of CO₂ capture is gained from building chemical plants and from over 50 years experience in the supply of gas scrubbers. Linde's declared aim is to utilize its technologies in CO₂-reduction applications and to become an expert partner in this field for energy utilities and other industries.

Plant concept and development

The concept behind the design of the CO₂-pilot plant concept is to guarantee reliable trial operations. The plant has been constructed in stainless steel to minimize the risk of corrosion. The plant is highly instrumented to provide a high level of process monitoring and to ensure trouble-free operation with a smooth interaction of the material flows.

The introduction of various material samples to the plant provides an insight into the stability of these materials for future projects.

From the experience gained in this initial stage, further development can be carried out into the technology for a larger demonstration system, and then for a major commercial plant, for the optimal treatment of the flue gas stream of a large-scale power station.



CO₂ plant of the Linde Group



Plant for chemical scrubbing

The large volumes of flue gases involved are beyond the capacity limits of currently available plant and equipment. For the present, the market is not able to provide equipment of the required size and so existing process technologies (e.g. for dividing the sub-streams to the scrubbing columns) require revision or to be developed from first principles.

As a result it becomes necessary to design and test equipment for chemical scrubbers of unprecedented dimensions. Besides the required selection in classic metal materials, Linde is investigating the use of concrete and GFRP which are already used in the power-plant area.

Linde is also developing concepts to dry and compress CO₂ after scrubbing.

The economic efficiency of CO₂ capture is of utmost importance in the development of this plant type. Such a plant can only be profitably operated if the costs do not exceed the price of CO₂-emission rights. Linde is convinced it can find solutions to meet these challenges.

THE CLEAN COAL STRATEGY OF RWE POWER

The CO₂-scrubbing pilot plant at Niederaussem is an important part of RWE Power's clean-coal strategy, which consists of three development and time horizons chosen to achieve ambitious climate-protection targets.



The projects in the first horizon encompass the present renewal of RWE Power's power plant fleet by building and deploying modern, highly efficient and, hence, more climate-friendly lignite- and hard-coal-fired units.

The second time horizon extends to about 2015 and aims at even better utilization of coal as a fuel. This purpose is served, e.g., by pre-drying the lignite in WTA systems and by so-called 700°C power plant

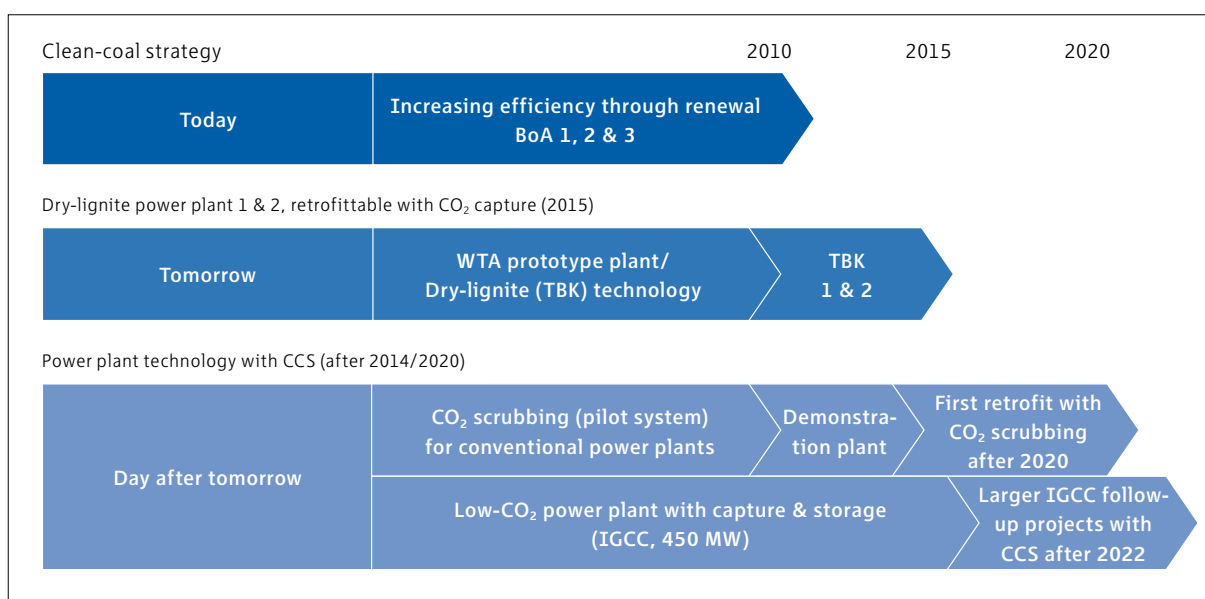
technology. What matters here is the implementation of higher process parameters with a higher steam temperature (up to 700°C) and higher steam pressures (up to 350 bar). This requires above all, the development and deployment of new materials. Both dry-lignite power stations and the 700°C power plant technology enable future coal-based power plants to leapfrog the 50 percent efficiency hurdle and, hence, obtain even lower CO₂ emissions.

The third horizon is geared to the period from 2015 to 2020 and aims at commercial-scale CCS trialling. Parallel to the CO₂-scrubbing project at the Niederaussem Coal Innovation Centre, RWE Power has started a beacon project at the Goldenberg location in North Rhine-Westphalia: the so-called IGCC-CCS project. The abbreviation stands for Integrated Gasification Combined Cycle with Carbon Capture and Storage.

There, CO₂ capture is not downstream, but a central component of the overall process. In coal gasification, a mixture of hydrogen and carbon dioxide is produced after a further interim step. The CO₂ can easily be separated from this mixture, and then compressed and transported to a storage facility by pipeline. The remaining hydrogen is burned in a gas turbine to generate electricity. The waste heat

drives a steam turbine in a downstream power-plant process.

As an alternative to power generation, the hydrogen – undergoing further conversion steps – can be deployed to make, e.g., synthetic natural gas or motor fuels, like diesel and crude oil. So, with the construction and operation of the IGCC-CCS demonstration power plant, RWE Power is becoming flexible beyond electricity generation and able to respond to new market opportunities. For pinpointed conversion of lignite into gas, IGCC technology can be an interesting option in the event of oil-supply bottlenecks. Here, we are providing an answer to the question of long-term energy security.



OUTLOOK

Trial operations at the Niederaussem pilot plant are due to run until the end of 2010. Using the technical and economic results of the 18-month investigation program, RWE Power will take a decision on the construction of a large demonstration system with a capture capacity of up to 200,000 tonnes of CO₂ per year.

In this setting, the entire technology chain – CO₂ scrubbing, transport, storage – is then to be implemented in practice and trialled. One possible location here is RWE's planned hard coal-based power plant at Eemshaven, Netherlands.

As total budget for the development project "CO₂ scrubbing", RWE Power has penciled in € 80 million. At the end of the project, CO₂ flue-gas scrubbing is to be so refined, adapted and optimized for the requirements of power plant operations that it can be used after 2020 on a commercial scale for existing or new coal-fired power stations. These stations

are currently replacing the older power plant generation and offer the necessary technical and economic prerequisites for retrofitting with CO₂ flue-gas scrubbers. In the near future already, these new, trend-setting technologies will make an important contribution to environmental and climate protection, while helping secure a long-term power supply for the population.



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