



# CCS R&D PROGRAMME ANNUAL REPORT 2010



# CONTENT

Words from the CCS R&D Programme manager .....	4-5
Vattenfall and CCS .....	6-9

## **Presentation of the Sub-Projects**

Sub-Project Capture.....	10-11
Sub-Project Storage and Transportation .....	12-13
Support Project Environment.....	14

## **Presentation of twelve Projects**

Pilot Plant in Schwarze Pumpe.....	16-17
A Pilot Plant for Pre-Combustion CO <sub>2</sub> Capture.....	18-19
CCPilot100+ - Post-combustion Pilot Plant Project.....	20
OxyCoal UK Phase 2 Successfully completed.....	21
R&D on Environmental Impact of Amine Solvents.....	22
SO <sub>x</sub> and NO <sub>x</sub> in the CO <sub>2</sub> -processing Unit.....	23
Managing reservoir models for the Geological Storage of CO <sub>2</sub> .....	24
Reservoir and Cap Rock Response to CO <sub>2</sub> Storage.....	26
Feed Study of a CO <sub>2</sub> Pipeline.....	27
Vattenfall's View on CO <sub>2</sub> Transport Established .....	28
Groundwater Model in Vedsted .....	30
Potential Environmental Impact of CCS.....	32

## **Outlook**

Outlook 2011.....	34-35
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## **CCS R&D Projects**

Ongoing Projects 2010 .....	36-39
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## WORDS FROM THE CCS R&D PROGRAMME MANAGER



Göran Lindgren,  
Head of CCS R&D,  
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Vattenfall's CCS R&D Programme completed about 70 projects in 2010. A lot of interesting results have been achieved within our programme, as well as in additional CCS deployment projects directly funded by business units. A number of these projects are highlighted in this annual report.

It is essential that results from Vattenfall's CCS R&D Programme are synchronised and incorporated in the parallel deployment efforts that are underway. For this reason, a new organisation for CCS R&D was implemented in end of 2010. This new organisation is presented in other parts of this publication. The primary advantage of the new organisation is that all CCS R&D is assembled into one unit, which strengthens the coordination between different R&D activities and formally allocates the responsibility within a single organisational unit. However, detailed R&D management is performed regionally to ensure close alignment with production when implementing new technology into generation-scale demo projects and business operations.

Vattenfall has continuously advanced in its plans to erect capture demonstration plants. In Jämschwalde, Germany, considerable preparations to build a demo plant have already been made. The design of the demo plant is highly dependent on support from R&D to make a proper technical upscale of the technology.

Vattenfall's R&D programme comprises all the capture technologies: Oxyfuel, Precombustion and Postcombustion. R&D for the longer perspective is also performed concerning membrane applications and Chemical Looping Combustion. The tests at the Oxyfuel pilot plant in Schwarze Pumpe have been successfully underway for more than two years. During 2010, several burners were tested. Furthermore, a new unit was installed at the plant to treat a slipstream of the flue gases from the pilot plant in order to purify carbon dioxide. The installation, which will be put into operation in

2011, is intended to achieve a higher capture rate and lower energy consumption. A two-year test programme will be carried out.

In 2010, Vattenfall constructed a Precombustion plant in Buggenum, the Netherlands, where coal gasification technology will be used. The plant will be ready for tests in March 2011. The trial in Buggenum will last at least two years.

In Renfrew, UK, we have participated in trials on another Oxyfuel project called OxyCoal UK, led by Doosan Babcock. The investigations were finalised in 2010 and the results are very promising. Through this project we have studied other variables than those in our own pilot plant at Schwarze Pumpe. The results from the OxyCoal UK project have broadened our minds and given us a better understanding of combustion with other fuels and with other technical solutions than those studied at Schwarze Pumpe.

In order to validate the Postcombustion capture technology, the R&D programme has been engaged in collaboration with other companies to design, build and operate a slipstream Postcombustion pilot plant, called CCPilot100+ in Ferrybridge, UK. This is done in a three-party collaboration with SSE (Scottish and Southern Energy) and Doosan Babcock that is supported by the UK Technology Strategy Board. The plant will begin operating in 2011 and the tests will continue until 2013.

New innovative methods of capturing CO<sub>2</sub> are of great interest to Vattenfall. We work broadly to promote and monitor the development of the Chemical Looping Combustion (CLC) technology. Since 2008, Vattenfall has been involved in the EU-funded ECLAIR project, which includes a test plant at the Technical University of Darmstadt, Germany, for the combustion of conventional pulverized coal. The first tests for the whole reactor system are scheduled to begin early in 2011.

The geological storage of carbon dioxide is a crucial issue. Legislation on storage is being drawn up within the EU at the moment, and Vattenfall follows the process with great interest. We have a continuous dialogue with the inhabitants in the area where storage can be an option and work proactively in the field of transport and storage. The scope of activities in this respect is wide. We conduct research to develop tools for topics like site suitability and HSE (Health, Safety, Environment). Efforts are now focussed on different design solutions and on resolving important issues on a more detailed level.

A retrospective view of 2010 shows that Vattenfall's CCS R&D programme has been engaged in a great number of activities, including partnership in EU co-funded projects and joint industrial projects. The projects will continue in this direction and in the future pay more attention to issues relating to transport and storage. EU supports the development of CCS, mainly by funding demonstration plants. Vattenfall's R&D programme has delivered important input for developing this funding scheme by providing a broad range of options for consideration. In the future, our CCS R&D will become much more focussed on near-term support to our demonstration plants. Vattenfall's CCS R&D is approaching a position where the technology is validated. Further validation is needed during the years to come. In 2010, we made significant improvements and came closer to our goal of deploying the generation-scale demo plants in a near future.

I hope you will enjoy reading this annual report and find it interesting!



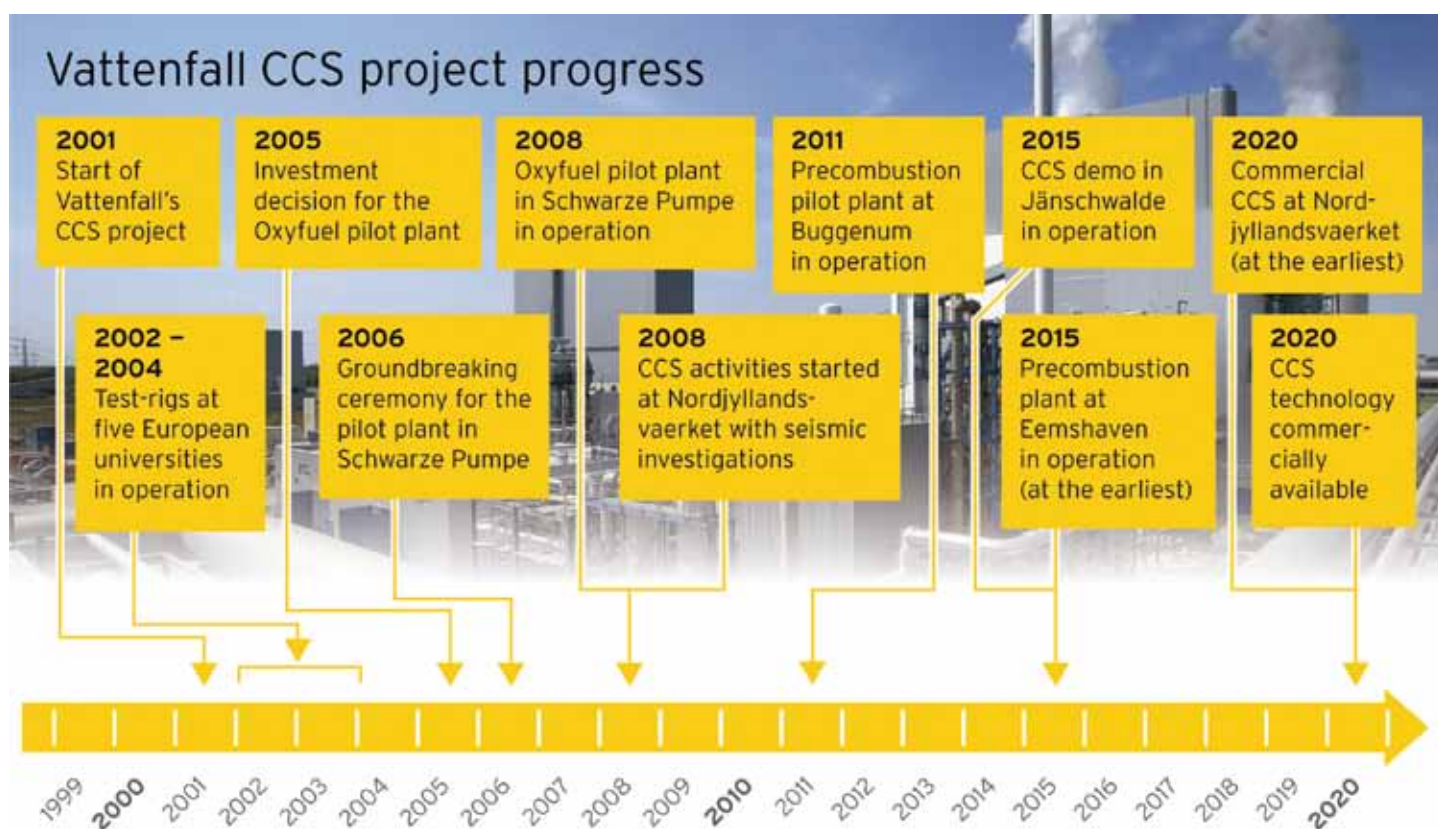
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# VATTENFALL AND CCS

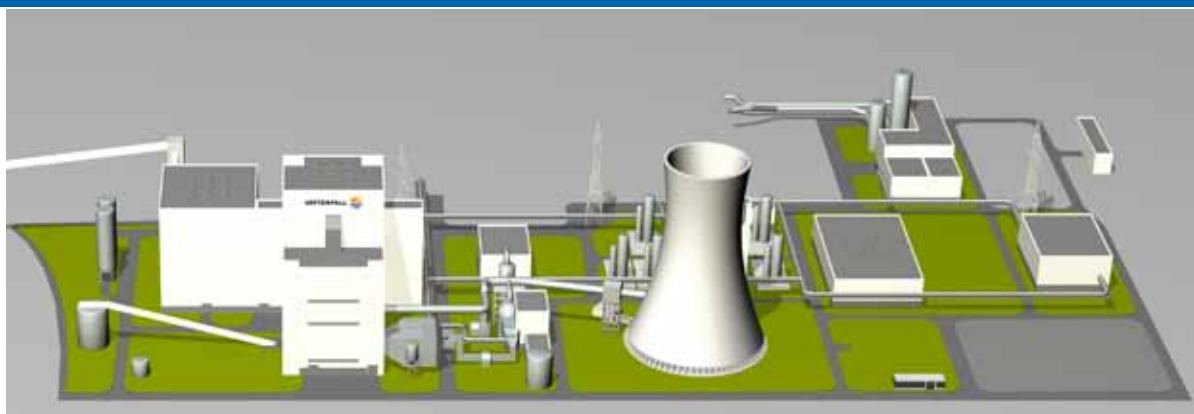
Vattenfall believes that Carbon Capture and Storage (CCS) will become a reality and that the technology will be commercially viable by 2020. The components involved in CCS already work and are in operation in various applications around the world. However, the capture, transportation and storage techniques have yet to be integrated in a way that delivers large-scale CO<sub>2</sub> abatement in commercial electricity generation. Vattenfall will now integrate these technologies at large demonstration plants and is working with stakeholders to develop the social, legal, and financial conditions for commercial deployment within ten years.

Coal still constitutes the basis of electricity generation in most European countries, and given these countries' energy policies it is likely to remain an important energy source for some time. At the same time, Europe's goals regarding climate

change require a drastic reduction of CO<sub>2</sub> emissions. Since fossil-fuel dependency and reductions of CO<sub>2</sub> have to be handled in parallel, Vattenfall sees CCS as an important solution. The idea with CCS is to capture CO<sub>2</sub> from coal-fired



Outline of the demonstration plant in Jämschalde. Coal is fed from the left to the new oxyfuel boiler, via the lignite dryer at the far left. The turbine island can be seen behind the boiler. The air separation unit is located behind the cooling tower. The Post-combustion unit can be found at the top right.



power plants, compress it to a liquid and permanently store it deep underground. Suitable storage sites are natural rock formations thousands of metres below the surface, which are similar to natural oil and gas reservoirs. CCS is not a substitute for renewable energy sources; we will need all the tools that have the potential to reduce emissions.

#### **The road to commercial plants in operation**

The goal for Vattenfall's CCS R&D Programme is to push the development of commercial concepts for carbon capture and storage at coal-fired power plants, and to make sure that CCS is available to Vattenfall by 2020. This research and development is a long-term commitment. Bringing an idea from project inception to commercial realisation often takes 10-30 years. Vattenfall started its CCS activities as an R&D project already in 2001.

The work started with GAP analyses, desk-top studies and conceptual investigations. Advanced cooperation with universities in Germany and Sweden was initiated and test rigs for studies of Oxyfuel combustion were constructed. The test rigs have answered many questions regarding combustion fundamentals, but to gain real operational experience and test material and process components, larger-scale plants are required.

#### **Pilot plants and investigation of storage**

The 30 MWth Schwarze Pumpe pilot plant in Germany was inaugurated in September 2008. It is the first pilot plant in the world to use the Oxyfuel combustion method and include all parts of the process, from air separation to CO<sub>2</sub> compression. The test activities in Schwarze Pumpe began in 2008 and continue to provide important input to the engineering of the demonstration plant in Jämschalde, which is the next step and will also use the Oxyfuel technology.

At Vattenfall's Willem-Alexander power plant in Buggenum in the Netherlands, another pilot plant will be inaugurated in early 2011. This pilot will test

the Precombustion capture of CO<sub>2</sub> in combination with integrated gasification combined-cycle technology.

The pilot plant in Buggenum will support the further development and implementation of this carbon capture approach on the demonstration and commercial scales, particularly at the planned facility at the Magnum plant.

During 2010, Vattenfall was an active partner in a new British cooperation project for pilot-scale tests of the Postcombustion technology, CCPilot 100+.

This means that Vattenfall now has first hand information from tests on a relevant scale of all three capture technologies. The more capture technologies that reach commercial maturity, the more options Vattenfall and others will have for their plants going forward.

So far, no CO<sub>2</sub> from the pilots has been injected into any storage formation. Instead, some of it has been further cleaned and sold as industrial gas. Vattenfall's ambition is to work together with Gaz de France to use future captured CO<sub>2</sub> from the Schwarze Pumpe pilot plant for enhanced gas recovery at the depleted Altmark gas field. Vattenfall is also working in the EU-cofunded research project (CO2SINK) on saline aquifer storage in Ketzin. Both of these projects are awaiting ratification of the new CCS legislation in Germany.

#### **Demonstration plants**

The technologies tested at Vattenfall's pilot plants will have to be demonstrated on a larger scale before they can be commercialised. Vattenfall is developing demonstration options in Jämschalde, Germany, and at the Magnum plant in the Netherlands. Vattenfall estimates that the investment costs of the demonstration plant in Jämschalde will reach € 1.5 billion. It has earlier been announced that the EU would support this investment with € 180 million in funding from the European Energy Programme for Recovery (EEPR). ►

The electrical power capacity of the demonstration plant will be approximately 300 MW. With a CO<sub>2</sub> capture rate of more than 90%, more than 1.6 million tonnes of CO<sub>2</sub> would be kept out of the atmosphere every year. The site preparation in Jämschalde has begun and the plant will be ready for operation in 2015. At Magnum, three natural gas combined-cycle plants will be built initially, with a second phase adding coal gasification, co-combustion of biomass and Precombustion capture of CO<sub>2</sub>.

Two potential saline aquifer storage structures, Birkholz and Neutrebbin, east of Berlin, are being investigated as potential storage sites for the

CO<sub>2</sub> captured at Jämschalde. Possible transport pipeline routes connecting the plant and the storage sites are being evaluated. The investigations will include detailed mapping of the structures and deep test wells to assess the suitability of the geology for future storage.

In the Netherlands, nearly depleted gas fields are being investigated as potential storage sites.

#### **Commercial plants in operation**

Vattenfall's goal is to push the development of commercial concepts for carbon capture and storage at coal-fired power plants and to have the technology available by 2020. Our plan is then



The CO<sub>2</sub> compression plant and intermediate storage tanks at the Oxyfuel pilot plant in Schwarze Pumpe.

to add full-scale CCS operation at the Nordjyllandsværket plant in Denmark. This was originally planned to be a demonstration project, in operation by 2014, but has been postponed due to financial restrictions. Instead, we plan to wait a couple of years with this plant and take advantage of the envisaged rapid development of capture technologies that will result from the work at our demonstration plants and other CCS sites around the world.

#### **Not only technological challenges**

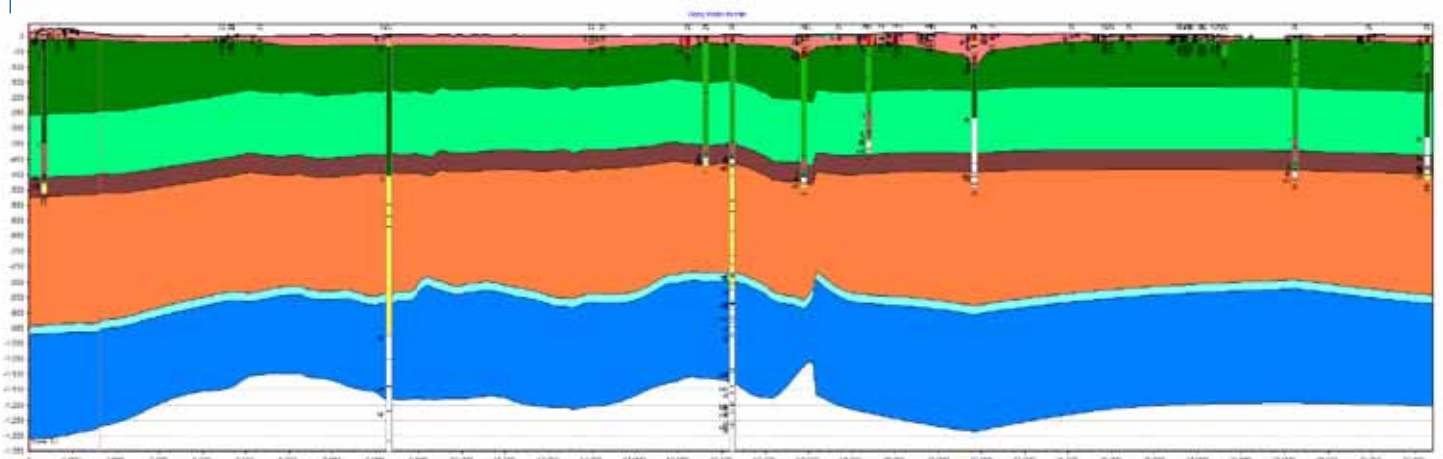
Parallel with the demonstration of the technical and financial feasibility of CCS, we must work with other stakeholders to create conditions that will allow the technology to be realised. This entails three interrelated challenges: building acceptance for the technology among local communities and society as a whole; developing legal frameworks that facilitate investment and manage risk; and establishing the financial incentives needed to bring the technology to market.

#### **R&D to support the CCS activities**

Since the start of the R&D project on CCS, engineers in Sweden and Germany have focused on the technological, environmental and social aspects of the entire chain of capturing, transporting and storing CO<sub>2</sub> from power plants. R&D has been carried out in broad cooperation with research institutes, universities, suppliers of technology and energy companies.

The focus right now is on supporting the demonstration projects in their efforts to take the technology from the pilot scale, where the technical abilities have been proven, to the demonstration scale, which is ten to twenty times larger and involves more and other challenges, not least financial, social and legal.

To be able to detect any impacts on the surrounding environment, we need to establish the natural levels and variations of CO<sub>2</sub> in the storage area. The figure shows a transect through a groundwater model for the potential Danish storage site in Vedsted.



## SUB-PROJECT CAPTURE

The activities within sub-project Capture are essential for achieving the commercialisation of CCS. Each year, a large number of projects are finalised that contribute to the development of different capture technologies. This brings us closer to a demonstration plant and eventually to the commercialisation phase. During 2010, the sub-project focused even more than in previous years on supporting Vattenfall's planned demonstration plants in Jämschwalde in Germany and Magnum in the Netherlands. As in previous years, the sub-project was led by Marie Anheden.

Capture R&D reduces the technical and financial risks associated with the implementation of the CO<sub>2</sub> capture technology by closely investigating critical areas of the capture processes. Capture is the largest sub-project within Vattenfall's CCS R&D Programme.

Capture technologies basically aim to produce a concentrated stream of CO<sub>2</sub> that can be transported to a suitable storage site. To achieve this, Vattenfall takes a broad approach in its research and studies many different technologies for cap-

turing CO<sub>2</sub>. There are three methods that stand out as available options for the implementation of the first generation of CCS plants around 2020-2025; Oxyfuel combustion, Postcombustion and Precombustion capture.

Benchmarking activities have shown that all three of these technologies have competitive advantages in different site-specific and commercial settings. Vattenfall is about to implement all three technologies in demonstration plants.

### **Large-scale validation important for scale-up**

Vattenfall has come far in the plans for its CCS demonstration plants. In Jämschwalde, site preparations have begun and the tendering processes for most large pieces of equipment are ongoing. These processes need support from the R&D activities in order to minimise technical and financial risks. The large-scale validation of the technology involved is therefore of the utmost importance.

Several capture projects focus on the large-scale validation of the different capture technologies, where the two most important are Vattenfall's own pilot plants in Schwarze Pumpe and in Buggenum. The Oxyfuel plant in Schwarze Pumpe, which has been running for more than two years now, provides an opportunity to test all the components of



Operator besides the coal silo at the oxyfuel pilot plant in Schwarze Pumpe.

Many different projects take place at DONG Energy's Postcombustion pilot plant in Esbjerg, e.g. for evaluating different amines for absorption and measuring emissions of amines. The picture shows equipment for the online emission measurement campaign: the line from the sample point after the absorber, which can be seen to the left, and the flask for the dilution of flue gases. The mass spectrometer is seen to the right.

Photo: Doosan Babcock.



the Oxyfuel technology. At the Willem-Alexander power plant at Buggenum in the Netherlands, Vattenfall has built a pilot plant for Precombustion that will be inaugurated in March 2011.

Vattenfall is and has been involved in pilot projects together with external parties as well. We are actively involved in the Postcombustion pilot project at the Ferrybridge power station in collaboration with SSE and Doosan Babcock. Also in the UK, Vattenfall has taken part in a project testing the Oxyfuel technology, OxyCoal UK. This was led by Doosan Babcock and finalised in 2010.

Vattenfall is also involved in several EU projects and cooperates with suppliers and other partners to share and exchange experience.

#### **Oxyfuel highlights 2010**

A study has been performed in collaboration with the gas company Air Liquide on process integration and improvements of the air separation unit, ASU, and the CO<sub>2</sub> processing unit, CPU, in the oxyfuel process. The results show that significant improvements are possible.

The continuous development of different modelling tools took place in 2010. One example is the initiated development of a simpler and faster modelling tool to support the first evaluation of design concepts for the boiler in Jämschalde.

Options for the removal of SO<sub>x</sub> and NO<sub>x</sub> in the Oxyfuel process have been identified and compared. Two models for simulating the behaviour of SO<sub>x</sub> and NO<sub>x</sub> have been developed, which should be validated against measurement data from the Oxyfuel pilot plant in Schwarze Pumpe and then used to predict the expected behaviour in different demo design options.

The construction of Air Products' slipstream pilot plant in Schwarze Pumpe has been completed, and the plant will be inaugurated in March 2011. The

slipstream pilot will provide important information about the process conditions and operation of a plant that closely resembles the design expected for the demo plant in Jämschalde.

Investigations of potential improvements of high-temperature oxygen transfer membranes for oxygen production in Oxyfuel plants, as a replacement of the conventional cryogenic ASU, have shown less potential than originally expected.

Chemical Looping Combustion is an emerging technology for CO<sub>2</sub> capture. Vattenfall is involved in the ongoing development work in EU projects and at European universities. Within the ECLAIR project, the construction of both the 100 kW and the 1 MW test plants at the Technical University of Chalmers and TU Darmstadt have been completed and commissioning is underway.

#### **Postcombustion highlights 2010**

At DONG Energy's coal-fired power plant in Esbjerg, projects relating to Postcombustion capture have been conducted for several years. Tests this year have led to the identification of an amine blend that shows significant improvements in energy consumption over the traditional MEA. The results are important since they show the potential of amines.

At the same plant, a project for measuring emissions of amines using different techniques has been initiated. The results will support the environmental application for the Jämschalde demonstration project.

Corrosion has been identified as a major risk in Postcombustion plants, and therefore Vattenfall has investigated different corrosion mechanisms and where in the plant major corrosion can be expected. Long-term tests have started in the pilot plant in Esbjerg, and further tests are planned in the Ferrybridge project. Results will be used to evaluate the material selection for the demonstration plant at Jämschalde.

# SUB-PROJECT STORAGE AND TRANSPORTATION

In 2010, the activities of the sub-project Storage and Transportation focused more on supporting the demonstration projects, site specific R&D and applied research. As in previous years, the sub-project was led by Christian Bernstone. Jenny-Ann Nilsson was responsible for transportation issues.

## Two-fold structure

As in previous years, the overall purpose of the sub-project is to investigate and develop concepts that can be applied to pilot and large-scale CCS demonstration projects and subsequent commercial deployment. The R&D performed within sub-project Storage and Transportation has a two-fold structure, where one focal point lies on direct R&D support to Vattenfall internal deployment projects, and the other focal point is on building expertise through co-operation with international networks, industrial players and world-class scientists.

## Birkholz and Neutrebbin

### - Potential saline aquifer storage structures

A three-phase exploration programme for the CO<sub>2</sub> storage sites Birkholz and Neutrebbin began in 2009 and will be continued the coming years. The aim is to investigate the potential of these sites for the storage of carbon dioxide from Vattenfall's CCS demonstration project in Jämschalde. The investigations will include detailed mapping of the structures and deep test wells to assess the suitability of the geology for future storage. Possible transport pipeline routes connecting the plants and storage sites are also being evaluated.



The impact that pressure, temperature and the related phase behaviour of the CO<sub>2</sub> flow in different operational phases could have on the technical design of the pipeline and the injection well was evaluated in 2010.

The CCS R&D Programme supported the German activities in several ways during 2010. Work is underway to develop a base-line monitoring plan for the Birkholz structure, and a second risk assessment of the Birkholz storage project has been conducted. When injecting CO<sub>2</sub> into a structure, the formation pressure will rise locally. A study has been performed in order to model this pressure build-up and to find solutions on how to handle it.

A power plant with CO<sub>2</sub> capture will, as conventional power plants, be run in different operational modes; full load, part load and sudden changes in between, start-up, planned and unplanned shut-downs etc. The impact that pressure, temperature and the related phase behaviour of the CO<sub>2</sub> flow in these different operational phases could have on the technical design of the capture process, the pipeline and the injection well was evaluated in 2010.

### **Vedsted in Northern Denmark still an option**

Even though Vattenfall's plans for a CCS demonstration plant at Nordjyllandsværket have been shelved, it is a continued strategic interest to maintain the exploration licence of the Vedsted site, where the CO<sub>2</sub> storage was planned to take place. A number of supporting R&D activities for the Danish project were completed in 2010.

An in-depth interpretation of the 2D seismic data survey that was conducted in 2009 was made, in order to detail the location of the structure. Reservoir modelling has been accomplished to study the regional scale pressure effects of the CO<sub>2</sub> injection. A feasibility study of the possibility to monitor the

Vedsted structure using 4D seismic was carried out, as well as a feasibility test on satellite-based monitoring of ground motion in the area. In connection with the joint industry project CO2WELLS - where industry guidelines on well abandonment and well requalification are being defined - the Vedsted exploration well from 1958 was evaluated in a risk assessment.

### **Poland investigates long-term options**

Some R&D activities were performed in Poland too, although with a more long-term focus than earlier. Promising CCS scenarios for Vattenfall in Poland for the commercial phase beyond 2020 were investigated. The scenarios cover CO<sub>2</sub> capture facilities at two power plants in Warsaw, Siekierki and DeraD, and the most suitable storage options in the Warsaw region. Transport and environmental aspects have also been covered, as well as a financial evaluation of the scenarios.

### **Applied research**

Applied research can be described as activities performed within the borderland between fundamental research and implementation. Several such projects were completed in 2010, for example an identification of previously unmapped candidate near-shore aquifers in the Skagerrak region. This was conducted by the University of Oslo within the Skagerrak project.

A project on the visualisation of mechanisms involved in CO<sub>2</sub> injection and storage was concluded at the Heriot Watt University in Edinburgh, Scotland. This bilateral project shows good results with important information on ways of enhancing the dissolution of CO<sub>2</sub> into the formation water.

A study covering the state-of-the-art in diamond-core drilling systems shows important benefits in applying this technique for cost-effective and low environmental impact drillings for exploration purposes, e.g. for the characterisation of storage sites and for monitoring wells.

Thorough investigations must be undertaken in order to establish a safe location for CO<sub>2</sub> storage. If a site proves to be unsafe, no CO<sub>2</sub> will ever be stored there. CO<sub>2</sub> occurs naturally in the earth's crust and at some places around the world there is a natural leakage, which can result in wells with naturally sparkling water. Storage sites in these areas would never be chosen for CCS projects. The picture shows the ruins of a factory for bottled, naturally-sparkling water in the Azores.



Photo: Sara McGowan



When planning for a new power plant with CCS, it will be crucial to show that CCS will not cause any adverse impacts on the environment; neither on people, land nor water.

## SUPPORT PROJECT ENVIRONMENT

The general purpose of the CCS R&D support project Environment is to provide knowledge and support in all areas connected to health, safety and the environment (HSE) for Vattenfall's CCS activities. Vattenfall has to show that CCS is a safe technology and that we manage HSE issues in a responsible way in order to receive permits for CCS operations. As in previous years, the support project was led by Magnus Pettersson and Sara McGowan.

The overall goal of CCS R&D Environment is to contribute to 100 %-successful permit processes when deploying CCS projects. Our HSE performance should meet, or be even better than, regulations and standards when CCS is implemented. Another goal is to generate high confidence in Vattenfall's CCS activities.

The activities within the support project Environment are subdivided into three main parts: long-term R&D, near-term R&D, which provide support to Vattenfall's CCS implementation projects, and international R&D projects. Environment acts as a support project to the sub-projects Capture and Storage & Transport and to Vattenfall's CCS implementation projects.

We perform continuous evaluation of the HSE risks associated with CCS and identify critical knowledge gaps. In order to close the identified knowledge gaps and to minimise HSE risks we perform R&D studies to update our knowledge, both through internal work and in co-operation with external partners. It is important that all our knowledge is verified by credible, independent and objective R&D results, for example from scientific EU projects.

A general acceptance that the technology will be safe is of major importance to a wide introduction of CCS. It will be crucial to show that CCS will not cause adverse environmental or health impacts. This will primarily be dependent on the operators choosing the right technology and sites, but also on

the HSE issues being managed in a responsible way. The general HSE assessments for CCS and also HSE assessments for specific CCS sites have to be communicated to the different stakeholders, such as the general public, site neighbours and authorities.

### Highlights 2010:

Updated versions of the Strategic Environmental Assessment of CCS and the report on critical HSE risks associated with CCS were produced in 2010. The Life Cycle Assessment results have been updated with new data for postcombustion and precombustion CO<sub>2</sub> capture scenarios.

Special reports on potential environmental impacts relating to the capture, transport and storage of CO<sub>2</sub> have been written. A benchmark study of environmental impact assessments in external CCS projects has been performed.

The current knowledge of HSE risks connected to amine solvent use in postcombustion CO<sub>2</sub> capture has been mapped and a strategy for how to move forward to close any remaining knowledge gaps has been drawn up.

In Denmark, Step 2 of 3 in the development of a groundwater model for the Danish storage site Vedsted has been completed. A groundwater model and a baseline/monitoring plan for the German storage site Birkholz have been designed. In Poland, an environmental screening of different CCS scenarios has been conducted.

IN 2010, AROUND 100 PROJECTS WERE FUNDED DIRECTLY UNDER THE CCS R&D PROGRAMME. SEVERAL ADDITIONAL PROJECTS WERE FUNDED DIRECTLY BY BUSINESS UNITS AND SYNCHRONISED UNDER THE CCS PROGRAMME FRAME WORK. ON THE FOLLOWING PAGES, THE CONTENT AND RESULTS OF TWELVE DIFFERENT PROJECTS ARE PRESENTED. THE PROJECTS HAVE BEEN SELECTED BY THE SUB-PROJECT MANAGERS AS ESPECIALLY INTERESTING, IMPORTANT OR EXCITING. A LIST OF ALL THE PROJECTS FUNDED BY THE PROGRAMME, INCLUDING A CONTACT PERSON, CAN BE FOUND AT THE END OF THIS ANNUAL REPORT.



## PILOT PLANT IN SCHWARZE PUMPE

Inaugurated in 2008, the pilot plant in Schwarze Pumpe has been running for more than 9 300 hours and has produced more than 4 300 tonnes of liquid CO<sub>2</sub>. But not only CO<sub>2</sub> is produced in the plant; a lot of knowledge and operational experience is also being generated.

For more than two years now, test measurements have been performed in all parts of the pilot plant. The tests are performed in so-called test campaigns. The length of each test campaign depends on the scope and can last a few weeks or a couple of months. Every test campaign involves tests both in air firing and in oxyfuel firing.

Tests are executed by several parties. These of course include teams from Vattenfall, but also the technology suppliers, universities and research institutes are to a lesser extent involved in measurement activities and in analysing and interpreting the results.

The heart of the process is the boiler, where the burner has the key role when the lignite is combusted. This must take place as efficiently as possible, both in air operation and in oxyfuel mode, where the oxidant is a mixture of oxygen and recirculated CO<sub>2</sub>. During 2010, two different oxyfuel burners were tested in the pilot plant, one from Alstom and one from Hitachi Power Europe. The tests performed have focused on emission formation and destruction and on characterising heat transfer as a function of different operating conditions. Data has been collected to support validation of design and process simulation tools.

### Material tests

It is of the utmost importance to identify materials that can cope with the environment that is created within the furnace and the downstream flue

gas canal during oxyfuel combustion. Corrosion behaviour and other mechanisms that influence the material service length differ in oxyfuel combustion in comparison to conventional coal firing. Extensive knowledge about materials that are competitive both from a cost and availability perspective is essential.

One difference in comparison to conventional combustion is the significantly higher concentration of CO<sub>2</sub> in the flue gases. Under certain conditions this may cause so-called carburisation of the alloys in super heaters and water walls. Carburisation is a phenomenon where the carbon in carbon-rich atmospheres reacts with the metal. As an example, CO could react with iron, forming iron carbide, Fe<sub>3</sub>C, which is hard and brittle. This embrittlement of the metal can in the long run lead to the failure of components.

Another reason for the increased risk of corrosion in the oxyfuel process is the recycling of parts of the flue gases. This gives increased concentrations of corrosive species, such as SO<sub>x</sub> and NO<sub>x</sub>, leading to increased corrosion.

Important findings are that certain alloys do resist the above mechanisms and that the material selection must be made much more carefully than for conventional coal-fired power plants.

### Other results

Analyses of the performance of the ESP (elec-

trostatic precipitator) show that the ESP is an excellent device for the removal of ash, also from oxyfuel combustion. The ash is properly charged and removed and no evidence of the damaging phenomena back corona has been observed.

Tests have also been performed in the wet-scrubbing, flue-gas desulphurisation process, in order to investigate the removal efficiency of  $\text{SO}_x$  and other acidic components. The slurry chemistry and gypsum quality have also been studied.

The water produced in the process is removed in a flue gas condenser (FGC). The chosen design has turned out to be inadequate for the scale-up to a demonstration plant, as the performance is not good enough in part-load operation. At full load, the FGC removes the water and lowers the temperature of the flue gas as required.

Operator next to the newly-installed unit for testing new technology for  $\text{CO}_2$  purification



Many more conclusions have been drawn from the test results produced at Schwarze Pumpe, but also many new questions have been raised. The operations and the tests will hopefully continue for two more years.

#### **Additional pilot plant installed in Schwarze Pumpe**

In autumn 2010, a new unit was placed along the west side of the Oxyfuel pilot plant. The US gas company Air Products built a pilot designed to purify the raw  $\text{CO}_2$  from an oxyfuel fired system. The new unit utilises a slip stream of the flue gases from the oxyfuel pilot plant, taken out just after the particle removal.

The technology uses three concepts that together could lead to an optimised, low-cost, high-efficiency oxyfuel  $\text{CO}_2$  compression and purification plant.

The core of the system is the low-temperature partial condensation process used to remove the atmospheric gases nitrogen, oxygen and argon from the  $\text{CO}_2$ . The key to the efficiency of this low-temperature process is the refrigerant. Rather than using a conventional ammonia cycle, here the  $\text{CO}_2$  product itself is used to cool the raw  $\text{CO}_2$ . This design could lead to significant power savings if applied to commercial-scale plants.

Maybe the most exciting part of the new unit is the so-called sour compression process, which inherently removes  $\text{SO}_x$  and  $\text{NO}_x$ . During compression to 30 bar, any  $\text{SO}_x$  and  $\text{NO}_x$  in the raw  $\text{CO}_2$  will react to form acid. This could be bad news if it happens unexpectedly, or in the wrong place, but the newly-installed unit utilises these sour compression reactions in a configuration that controls the formation of acids within two vapour liquid contacting columns. This leads to a method that can be used to remove  $\text{SO}_x$  and  $\text{NO}_x$  from the raw  $\text{CO}_2$  stream, potentially saving in more expensive upstream control options and minimizing potential downstream corrosion.

The third part of the new unit is a membrane to recover  $\text{CO}_2$  and oxygen. It is placed on the vent gas stream that mainly consists of argon, nitrogen and oxygen, but also contains  $\text{CO}_2$ . The membrane separates the  $\text{CO}_2$ , but as a bonus it also recovers oxygen, which, once recovered to the boiler with the co-captured  $\text{CO}_2$ , reduces the amount of oxygen required from the air separation unit, making the ASU smaller and reducing the power required to produce the oxygen.

# CO<sub>2</sub> CATCH-UP PROJECT IN BUGGENUM: A PILOT PLANT FOR PRE-COMBUSTION CO<sub>2</sub> CAPTURE

Buggenum, in the Dutch province of Limburg, is the location of Vattenfall's Willem-Alexander power plant, which is based on the Integrated Gasification Combined Cycle (IGCC) technology. IGCC enables application of pre-combustion CO<sub>2</sub> capture. A pilot plant, which is part of the CO<sub>2</sub> Catch-up Project, has recently been constructed for monitoring and optimising the capture process. The project was not formally a part of the CCS R&D programme during 2010, but when this report is published the CO<sub>2</sub> Catch-up Project and NUON's CCS R&D activities will be a part of the Group programme.

The construction work for the 253 MW Willem-Alexander power plant was commenced in 1990. It was a unique plant at the time, because it was the first IGCC coal-fired power plant in the world. The installation has been in operation since the end of 1993, and since 2001 biomass is co-gasified.

In comparison with conventional coal-fired power plants, IGCC has the advantage of low SO<sub>x</sub>, NO<sub>x</sub>, particles and mercury emissions. In order to reduce CO<sub>2</sub> emissions, pre-combustion CO<sub>2</sub> capture can be applied.

## **The CO<sub>2</sub> Catch-up pilot plant**

The Catch-up Project started in 2008 and the construction of the CO<sub>2</sub> capture pilot plant started in 2010, with commissioning during autumn of the same year. The inauguration is planned for the beginning of 2011 and the first test results are expected during the second quarter of the same year. The pilot plant will be in operation for two years to gather the necessary knowledge and experience for full-scale CO<sub>2</sub> capture applications in the CCS demonstration plant Magnum II.

## **CO<sub>2</sub> Catch-up R&D programme**

In parallel with the development, realisation and operation of the pilot plant, a test and R&D programme has been initiated together with Delft Uni-

versity of Technology, the Energy Research Centre of the Netherlands (ECN) and energy consultants from the company KEMA.

In addition to the pilot plant test programme, which involves execution of the test runs, a test support programme has been started for laboratory tests and the development of models to simulate and understand the processes occurring during pilot operation. Moreover, an R&D programme has been set up with several PhD projects looking for future CO<sub>2</sub> capture technologies that could be applied in the next generation of gasification plants. The test and R&D programme is divided into the following four work packages: Plant operation and optimisation, Water-gas shift section, CO<sub>2</sub> absorption section, and Fouling and corrosion.

## **Activities in 2010**

During 2010, three main tasks were performed within the Catch-up project. The first was the development of mathematical models, which will help explain phenomena observed during plant operation. The second was to define specific test objectives and the scope for test runs to be executed during plant operation, mainly for validation. The third task was the execution of laboratory experiments to determine the activity, selectivity and stability of different water-gas shift catalysts

Web cam photo of the pilot plant

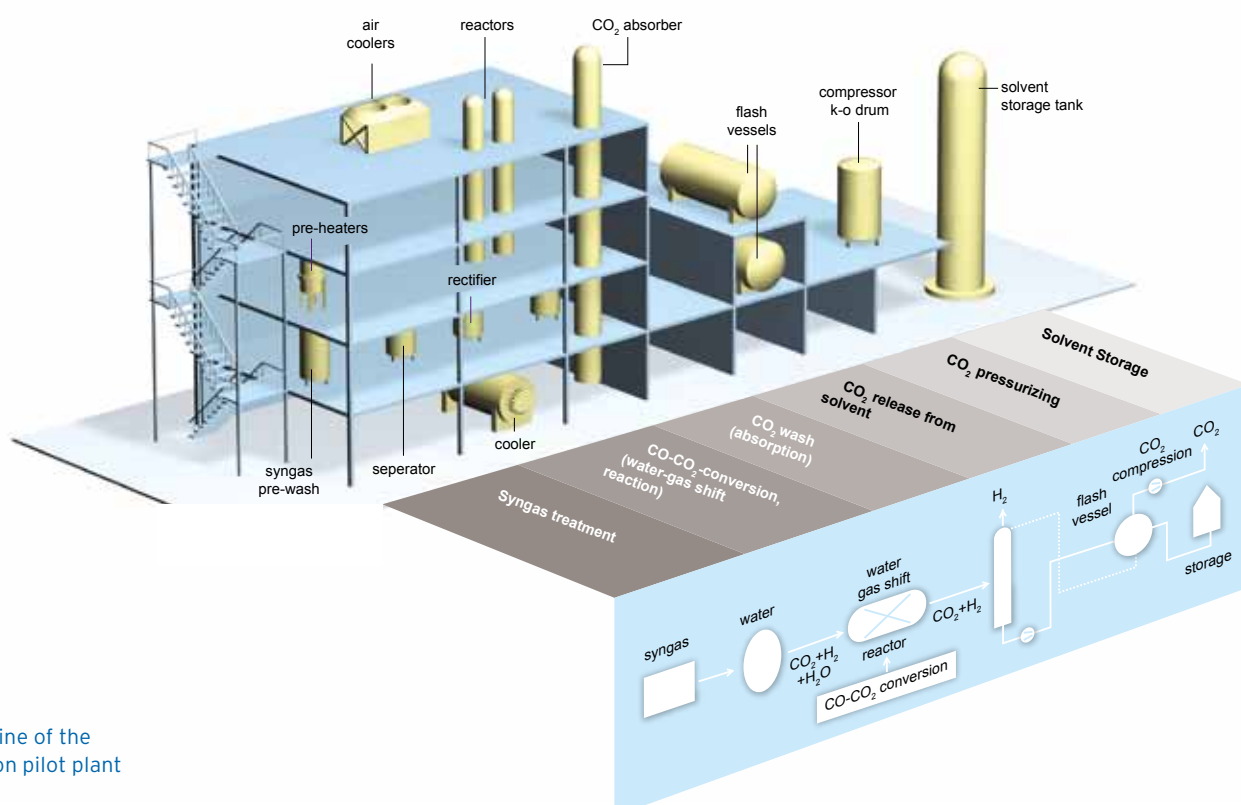


and the effects of aging, pressure, sulphur concentration and the H<sub>2</sub>O:CO ratio.

#### Considerations for economic viability

Although CO<sub>2</sub> capture has never been applied in combination with an IGCC unit, many of the elements present in the CO<sub>2</sub> capture scheme (water-gas shift, CO<sub>2</sub>-H<sub>2</sub> separation) have been proven in the chemical industry, although in a slightly different configuration due to the different purpose of CO<sub>2</sub> capture. In addition, the mode of operation in the

chemical industry is different than in the power sector; in the latter, the load of the water-gas shift and CO<sub>2</sub> capture unit should be able to follow the sometimes frequent load changes in the power plant. However, as the energy consumption associated with the water-gas shift reaction and CO<sub>2</sub> absorption is significant, the main challenge lies in minimizing the specific energy consumption and costs per tonne of avoided CO<sub>2</sub>. A challenge for IGCC with the CCS concept is the development of burners for the combustion of hydrogen-rich syngas.



Principal outline of the Precombustion pilot plant at Buggenum

# CCPILOT100+ – POSTCOMBUSTION PILOT PLANT PROJECT

In early 2010, Vattenfall became involved in a post-combustion pilot plant project at Ferrybridge power station in Yorkshire, UK. The Ferrybridge plant is located in the heart of one of England's most industrial and energy-intensive areas, which accounts for a large amount of the UK's CO<sub>2</sub> emissions. The carbon capture pilot is therefore a prioritized project for the development of a carbon-lean future.

Before Vattenfall joined this project, it was announced that Vattenfall had qualified for European funding to build and operate a large-scale demonstration plant including post-combustion CO<sub>2</sub> capture at its Jämschalde power plant in Germany. This was really good timing since the project will provide us with vital knowledge before moving up to the 12-times larger demonstration scale.

Around 100 tons of CO<sub>2</sub> will be captured per day from a flue gas slip-stream, corresponding to approximately 5 MW electric power, which will be extracted from the flue gases immediately downstream the newly-commissioned flue gas desulphurisation unit. An amine solution will be used to scrub the flue gas in a packed column, thus absorbing the CO<sub>2</sub> into the liquid. Later, in a separate column, the solvent will be boiled to release the CO<sub>2</sub> and thereafter recycled back into the absorber.

During the autumn, engineering work was concluded by Doosan Power Systems, which resulted in decisions regarding the process design and the equipment. The manufacture and construction teams are now making progress despite the harsh winter weather. The tie-ins for extracting the flue gases and returning the CO<sub>2</sub>-lean off-gases into the ducting before the stack have been mounted and all the foundations for the new ductwork and the

main plant area have been finalized. Steel support structures are being assembled on site. All other units and items have been contracted and are being manufactured with delivery dates in the winter of 2010/11 and the spring of 2011.

The CCPilot100+ project is a key project to close the gap between the years of R&D and the planned 50 MW demonstration plant in Jämschalde. Apart from the financial contribution of £4.5 million to the project, Vattenfall's main responsibility and focus is on testing the equipment performance, the materials, the off-streams and the dynamic operability of the process as a whole. The Vattenfall team is a mixture of personnel from the R&D, engineering and generation departments in Germany, Sweden and Denmark, and contributes actively to the planning and realisation of the project. Our staff will be onsite when the two-year period of operation and testing starts in the summer of 2011.

The main project partners are Scottish and Southern Energy (SSE), who own and operate the power plant, and Doosan Power Systems, who provide the capture technology. The £21 million project is also funded by the UK Department of Energy and Climate Change (DECC), the Technology Strategy Board and Northern Way.

Operational experience was an important outcome of the OxyCoal 2 project.



## OXYCOAL UK PHASE 2 SUCCESSFULLY COMPLETED

In 2010, the oxyfuel pilot plant project in which Vattenfall was involved in the UK was finalised. A total of 20 test days were accomplished in Doosan Babcock's 40 MW<sub>t</sub> test facility in Renfrew, Scotland.

Vattenfall participated in the OxyCoal UK collaboration, which was led by Doosan Babcock, part of Doosan Power Systems. In a first phase, the underpinning technologies of the oxyfuel process were studied and in Phase 2 the company modified its existing test facility by adding equipment for oxyfuel combustion purposes. The Clean Combustion Test Facility (CCTF) has successfully demonstrated a coal-fired oxyfuel combustion system of a type and size applicable to new builds and to the retrofit of advanced supercritical oxyfuel plants.

Having completed close to 100 individual tests, the firing trials in the CCTF have demonstrated the successful operation of the 40 MW<sub>t</sub> OxyCoal<sup>TM</sup> burner, both in air and in oxyfuel mode. Safe and stable operation has been achieved across a wide operational envelope. CO<sub>2</sub> concentrations of up to 85% (v/v dry) have been achieved at the economiser exit.

### Importance for Vattenfall

For Vattenfall, the tests in the CCTF at Renfrew are a good complement to the test activities in our own pilot plant at Schwarze Pumpe. We can make important comparisons and thereby be more certain about some of the findings. In the OxyCoal 2 project, bituminous coal was used as fuel, which is an important difference compared to Schwarze Pumpe, where we use lignite as fuel. Nevertheless, comparisons regarding combustion and heat transfer can be made and similarities and differences are noted.

Göran Lindgren, CCS R&D Programme Manager, expresses his delight: "We really appreciate the cooperation and the dialogue that we have had with Doosan Babcock and the other participants in the OxyCoal 2 project. Oxyfuel has yet again been validated on a large scale and we are convinced that it is a useful technology for a CCS demonstration plant."

### Conclusions drawn

In the OxyCoal 2 project, a lot of emphasis was placed on gaining oxyfuel operation experience. Flame stability, load turndown, start-up, shutdown and the transition between air- and oxyfuel-firing have been thoroughly investigated and demonstrated.

The combustion efficiency has been investigated by analysing the amount of unburned carbon in ash samples and the amount of carbon monoxide in the flue gases. The analyses show that the combustion efficiency under oxyfuel firing is comparable to that under air firing.

Analyses have also been made of heat flux and transfer, formation and removal of SO<sub>x</sub> and NO<sub>x</sub> and much more.

### Broad cooperation

Besides Vattenfall, Scottish and Southern Energy, E-On UK, DONG Energy, EdF, Air Products, Drax Power, Scottish Power and UK Coal sponsored the project. The University of Nottingham and Imperial College of London contributed knowledge and research. DECC, the UK Department of Energy and Climate Change, also gave the project financial support.

# R&D ON ENVIRONMENTAL IMPACT OF AMINE SOLVENTS

The Postcombustion technology for CO<sub>2</sub> capture (PCC) is one of the main technology options for the first commercial power plants with Carbon Capture and Storage (CCS).

Lately, it has been claimed that the use of amine-based solvents in the PCC process could result in emissions of substances potentially harmful to human health and to the environment. The groups of substances that are at the centre of this discussion are nitrosamines and nitramines. Specific substances within these groups may be toxic and carcinogenic.

The potentially harmful substances could be formed in the PCC process through degradation of the solvent and through reactions with flue gas components. It is expected that these substances may be present at extremely low concentration levels (ppb or ppt). Small amounts may be emitted via the treated flue gas to air or captured in other waste streams, such as waste water.

In order to better understand how to avoid any harmful impact on human health and the environment when using amine-based solvents in the PCC process, Vattenfall is engaged in many R&D activities within this area, as presented below.

## **Amine degradation in the PCC process**

The basic processes for amine degradation in the PCC process are known, but the exact reaction mechanisms are very complex and more knowledge is needed within this area. This knowledge is also supporting the development of mitigation methods to minimise emissions of harmful substances from the PCC process.

Another area for research is measurement methods - considering the extremely low concentration levels and that we have no exact knowledge of which individual substances will be present, measurements with reliable results are difficult to achieve. Vattenfall is therefore focusing research on improving our understanding of which sub-

stances may form and on suitable methodologies for detection and measurement.

During 2010, Vattenfall performed a study to map current knowledge within the areas of available amine solvents, amine degradation within the PCC process and in the environment, measurement methods, potential health and safety and environmental impacts, dispersion modelling and relevant legislation, together with a pre-study of process mitigation options for gaseous emissions.

An external study, performed by the Swedish Environmental Research Institute (IVL), has suggested suitable methods for measuring amine degradation products.

Vattenfall has also participated in the EU 7th framework programme project Cesar by running R&D activities in areas such as emission measurements and process optimisation at the PCC pilot plant in Esbjerg, Denmark. At the same pilot plant, an industry project focusing on emission measurements and establishing reliable measurement methods has been initiated.

## **Further reactions in the environment**

If amine solvents and their degradation products were emitted to the environment, further degradation may occur. More knowledge is needed to establish qualitative and quantitative data on final products and their fate in the environment. More knowledge is also needed on the toxicology of some of the potentially harmful amine substances that may end up in the environment as final products. Reliable toxicology data will help to guide authorities in setting limit values for emissions.

During 2010, Vattenfall participated in the so-called ADA 2010 project coordinated by Oslo University to study the reaction mechanisms of amine substances emitted to the atmosphere. We have also participated in the ExSIRA project coordinated by the Norwegian Institute for Air Research (NILU) to study toxicology, dispersion modelling and corrosion in connection with emissions of amine substances.

#### Safe and responsible handling

Based on the knowledge and information that is available today, we are convinced that organic amines can be used in a safe and responsible manner. However, we do not take anything for granted and this is why we are involved in the research presented above. Our ambition is to learn more and to improve the work environment for our employees, limit the already very small risks for our neighbours and safeguard the environmental performance in general.

## SO<sub>x</sub> AND NO<sub>x</sub> IN THE CO<sub>2</sub>-PROCESSING UNIT

A study to assess different options for the removal of the unwanted gases SO<sub>x</sub> and NO<sub>x</sub> has been finalised. Different technologies have been evaluated, in laboratory tests or on pilot scale and, although development is expected to continue, we can today identify the most promising combination for the removal of SO<sub>x</sub> and NO<sub>x</sub> in the oxyfuel process.

In conventional coal-fired power generation, SO<sub>x</sub> and NO<sub>x</sub> are major pollutants and are mainly regulated by limits set by the authorities. In addition, SO<sub>x</sub> is a major acidic gas component that should be controlled to prevent damage caused by deposits and corrosion. There are several mature technologies that are applied for de-SO<sub>x</sub> and de-NO<sub>x</sub> from the flue gases derived from combustion of coal. These include wet flue gas desulphurisation, FGD and selective catalytic and non-catalytic reduction of NO<sub>x</sub>, SCR and SNCR.

may be more important. Requirements set by the systems adopted for the transport and storage of the captured CO<sub>2</sub> may also play an important role.

#### Study on de-SO<sub>x</sub> and de-NO<sub>x</sub> performed

The oxyfuel process offers unique opportunities for an inherent removal of SO<sub>x</sub> and NO<sub>x</sub> and the performed study has aimed to evaluate different technical options.

The objectives of the project have been to compare new technical options, which could potentially be applied in demonstration plant applications, and to identify important issues that may affect the application of the new technical options. A better understanding of the principles and mechanisms of the processes in question has also been an objective for the study.

The work was initiated already in 2007, but the rapid technical development in the area has increased the scope each year. Practical experience from the CO<sub>2</sub> processing unit at Schwarze Pumpe has been used as important input to the study, although results from the pilot plant did not

Detail from the CO<sub>2</sub> compression unit in the oxyfuel pilot plant in Schwarze Pumpe



When power is generated using coal-fired oxyfuel combustion with carbon capture, the emissions to the atmosphere may not be a major issue. Instead, the requirements from downstream processes, i.e. the CO<sub>2</sub> purification and compression, and issues related to the oxyfuel combustion itself

become available until 2009. Six technical options for de-NO<sub>x</sub> and de-SO<sub>x</sub> in CO<sub>2</sub> process units have been reviewed and studied. The study has been performed by Vattenfall, but with input from both external suppliers and different universities.

#### **Conclusions and further work**

An important conclusion is that removal of NO<sub>x</sub> and SO<sub>x</sub> will be facilitated by the increased pressure. NO<sub>x</sub> and SO<sub>x</sub> will convert into more soluble components and can be washed out through wet scrubbing. This may involve some unwanted, liquid by-products that need to be handled.

Another important conclusion is that NO<sub>x</sub> and SO<sub>x</sub> are trapped in the dehydration and activated carbon beds. Activated carbon is used in the pilot plant in Schwarze Pumpe and this will most likely not be used or located in the same position in a larger-scale plant, but generally the adsorption of NO<sub>x</sub> and SO<sub>x</sub> by such filtration processes should be carefully considered, especially possible desorption processes.

As the oxyfuel technology is new, it is likely that the de-NO<sub>x</sub> and de-SO<sub>x</sub> technologies in the CO<sub>2</sub> compression part of the process will develop fur-

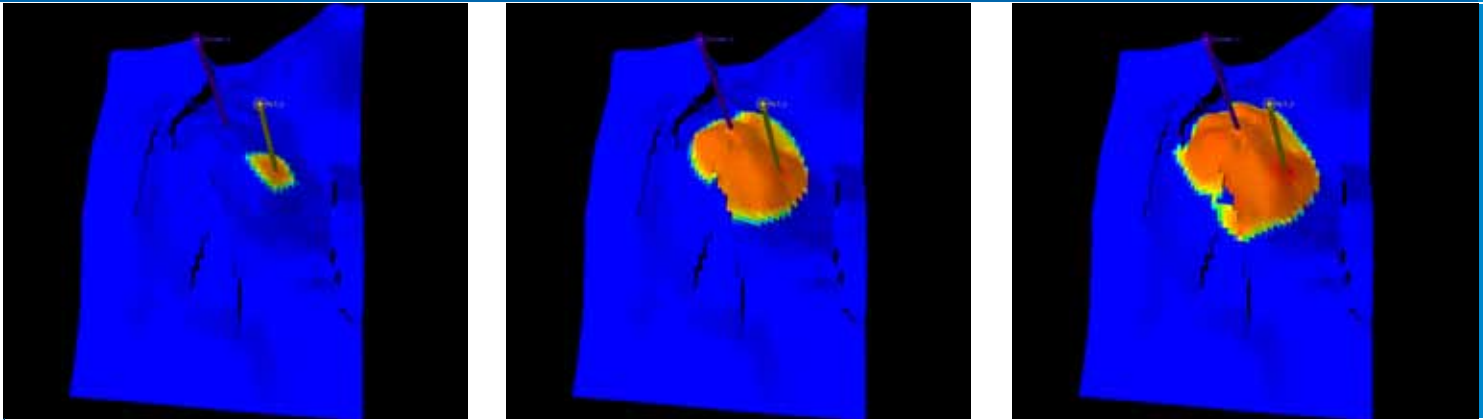
ther. It is desirable that this development takes the whole process into consideration including legal requirements, process operations and the handling of by-products.

With this reservation, the study concludes that the most promising option for the removal of SO<sub>x</sub> and NO<sub>x</sub> in the oxyfuel process is: (1) removal of SO<sub>x</sub> by up-stream flue gas cleaning processes, such as wet FGD, in order to remove most of the acidic gases and give rise to by-products that can easily be handled, (2) shorten the compression of wet gas by drying the flue gas together with (3) removal of NO<sub>x</sub> as early as possible in the early compression stages in order to reduce the risk of corrosion in compressors.

It is recommended to continue collaboration with the suppliers involved, in order to monitor further development and push it in the right direction. More work should be done to further understand the fundamental mechanisms and corrosion and material issues should be covered further. Techno-economic evaluation and optimisation concerning the de-NO<sub>x</sub> and de-SO<sub>x</sub> of the full oxyfuel process should be performed in order to evaluate the most promising options.

## MANAGING RESERVOIR MODELS FOR THE GEOLOGICAL STORAGE OF CO<sub>2</sub>

In oil and gas production, models of reservoirs have been used for decades in order to summarize reservoir knowledge and predict reservoir behaviour. The knowledge and research in this field are directly applicable to the reservoir modelling of CO<sub>2</sub> storage sites. However, there are significant differences between the concepts of producing from and injecting into a reservoir, especially in relation to the increased pressure in the reservoir caused by injection. Research on reservoir models is therefore undertaken with a special focus on CO<sub>2</sub> storage-related issues and a number of Vattenfall studies were performed in 2010.



The results show how the CO<sub>2</sub> plume spreads within the structure after 1, 20 and 40 years, respectively. It can clearly be seen that the plume migrates towards the crest of the structure, driven by buoyancy, although the injection well is situated elsewhere.

One of these studies focussed on the effects of geological anisotropy (properties that differ along different axes) on storage capacity and CO<sub>2</sub> plume development. To date, the reservoir models for Vedsted have worked with a sheet-like geology, where the sand and clay layers are of a uniform thickness throughout the model. This is a fair approximation to the regional geological interpretation and no well information is available on the local variation. In 2010, however, Vattenfall used a statistical approach to generate more realistic distributions of porosity and permeability in the layers. The results show how sensitive the CO<sub>2</sub> plume development is to these variations over time.

#### Boundary conditions important

Another study focussed on the regional effects caused by the lateral extension of the increased pressure following CO<sub>2</sub> injection. Vattenfall studied this effect in 2010 using the setting around the Vedsted site. The study was performed at the Geological Survey of Denmark and Greenland (GEUS) and has resulted in new knowledge on the factors that control pressure propagation. Pressure propagation appears to be only slightly sensitive to the geological anisotropy. Of much higher importance are the boundary conditions of the models, which relate closely to the injection scenario. Choosing the wrong boundaries for the model can result in an unrealistically high or low pressure build-up scenario on a regional scale.

These results relate to a study performed in 2010 by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover, Germany. In 2009, BGR performed a semi-regional characterization for Vattenfall defining spill-points and analysing fault zones for the Buntsandstein reservoir in the Birkholz Structure. The 2010 pressure development study used a similar geological setting with

injection in the Buntsandstein reservoir. However, the study used closed model boundaries and shows rather large pressure increases in structures neighbouring those where CO<sub>2</sub> injection took place. Furthermore, the pressure continues to increase for a long time after injection. In order to discuss these issues, Vattenfall invited BGR to a workshop in which GEUS also participated. There was clear agreement among all the parties involved that closed boundary conditions would cause the lateral pressure to behave in a way that is unrealistic for sheet-like geology such as that at Buntsandstein.

#### Different models required

As illustrated by the examples above, it is not possible to limit the model work to one model. First of all, the models must be developed and updated when new data is acquired. Such updates can lead to new levels of detailing or incorporate new knowledge that was not previously part of the model. For the reservoir model it is therefore of the utmost importance to work systematically with model management, using reference models with carefully assigned version numbers reflecting the current state of knowledge. Even when conducting careful model management it is not possible to integrate all the knowledge into one model. For example, the regional model is much larger than the reservoir model and in order to simulate flow the level of detail must be minimized. Apart from the reservoir models, a number of other models are related to CO<sub>2</sub> storage to account for other types of knowledge regarding reservoirs and layers, e.g. geomechanical models and groundwater models. Results from all these models are important for the planning and management of any storage site. Careful selections of area of interest, as well as software, are crucial for the successful integration of the knowledge represented by these models.

# RESERVOIR AND CAP ROCK RESPONSE TO CO<sub>2</sub> STORAGE

An important precondition for the success of Vattenfall's CCS project is the availability of sustainable storage alternatives. Vattenfall therefore has to investigate possible storage options in Europe. In this context, several underground sites in Denmark are believed to be optimum candidates for CO<sub>2</sub> storage. Here, Vattenfall has a particular interest in the Vedsted Structure close to the Nordjylland Power Station.

GEUS (Geological Survey of Denmark and Greenland) therefore approached Vattenfall and DONG energy in 2007 to initiate a project - AQUA-DK - that would investigate the possible impact and long-term effects of stored CO<sub>2</sub> on the relevant reservoir- and cap-rocks concerned. The project was finalized in 2010.

The project commenced in January 2008 with the set-up of batch experiments in the laboratory facilities at the British Geological Survey. Here, relevant rock material was placed in pressure vessels with simulated reservoir temperatures, pressures and formation water (brine) compositions.

There are no direct samples of the brine from the Vedsted structure. The sampling of brine was not a common procedure back in the fifties when the Vedsted structure was drilled for oil exploration purposes. It has nevertheless been possible to establish the likely fluid composition for this experiment based on analogue data from other sources in Denmark.

The rock samples were investigated under a microscope to examine the mineral assemblage - and to see if it would change on contact with CO<sub>2</sub>. The samples were also studied in electron microscopes to get an impression of how worn the mineral surfaces were, and if this would change after exposure to CO<sub>2</sub>. Furthermore, the rock was analysed chemically in order to establish exchanges in elements between the simulated brine and the rock samples.

Other components of the project were to fit and adjust models that describe the changes observed

in the laboratory and, furthermore, to predict what could be expected during long-term storage.

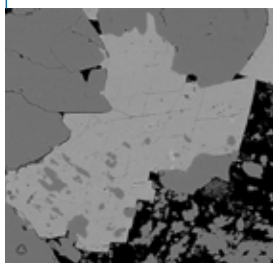
Seven samples of the fluid were then taken and analysed in intervals of up to 14 months exposure, while the samples of the rock were taken at the mid-term and at the end of exposure for analysis.

The results of the evaluation of the reservoir rock show that only the carbonate minerals are affected by the CO<sub>2</sub> enrichment, see figure here besides. The silicate minerals are not more etched or dissolved after than prior to the CO<sub>2</sub> experiments.

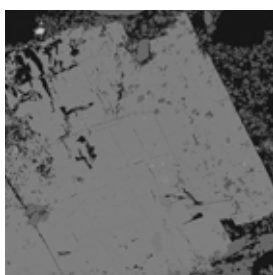
This is good news in the sense that the experiments show no expected reduction in the strength of the reservoir rock intended for the CO<sub>2</sub> storage. The fact that the silicate mineral system is stable also decreases the risk of a large degree of re-precipitation of new minerals, thereby reducing the permeability and injectivity.

The study also included an evaluation of the seal integrity. The results showed that the available cap rocks are very competent in terms of sufficient thickness, stable mineralogy, grain size, permeability and capillary properties. Furthermore, the liquid permeability and the threshold pressure for super critical CO<sub>2</sub> were also tested with good results. GEUS concluded that the relevant cap rock has excellent sealing properties. Another positive effect is that the CO<sub>2</sub> mineral interactions seem to decrease the porosity and thereby potentially improve the sealing capacity.

Ankerite is a calcium, iron, magnesium and manganese carbonate mineral and is affected by the CO<sub>2</sub> enrichment. The picture shows electron microscope pictures of ankerite before and after CO<sub>2</sub> exposure. In the "after" picture it can be seen that the mineral is dissolved from the left.



Before



After

# FEED STUDY OF A CO<sub>2</sub> PIPELINE

To fill gaps in our knowledge about pipeline systems for CO<sub>2</sub> transport, a so-called FEED study has been assigned to the Hungarian company Olajterv. The study will increase our knowledge on how a CCS pipeline transport system design could be realised, with prerequisites taken directly from the Jämschwalde demonstration plant project.

Late in 2010, a FEED study of a CO<sub>2</sub> pipeline was kicked off. Vattenfall has requested the Hungarian company Olajterv to perform the FEED study, which entails front end engineering and design and will be used to analyse various technical options for new developments with the objective of defining the facilities required.

## Gaps in knowledge

Although Vattenfall lately has added natural gas to its core business, the knowledge in the Group on gas and the transport of gas is limited. The knowledge of pipeline systems for CCS purposes is limited in Europe, as the application is relatively new here.

In order to increase our understanding of how a CCS pipeline transport system could be designed, the FEED study was suggested. It will also answer questions such as what demands are necessary when purchasing such a system and what the interface prerequisites that it is important to highlight for Vattenfall could be.

The objective of the study is to get a state-of-the-art system design using the supplier's earlier experience of designing a transport pipeline for dense phase CO<sub>2</sub>. Not only would this increase our understanding of what a CO<sub>2</sub> pipeline system demands, it would also highlight knowledge gaps that ought to be covered by the R&D programme.

The study should provide information on what features, auxiliary systems, valves and so on are needed to operate the CO<sub>2</sub> pipeline and also on the

preferred materials to be used for a CO<sub>2</sub> -pipeline system. The work should also include, for example, system design for both normal and abnormal operation. Hence, a service provider with hands-on experience in CO<sub>2</sub> pipeline design and construction is required.

## Direct connection to Demo Jämschwalde

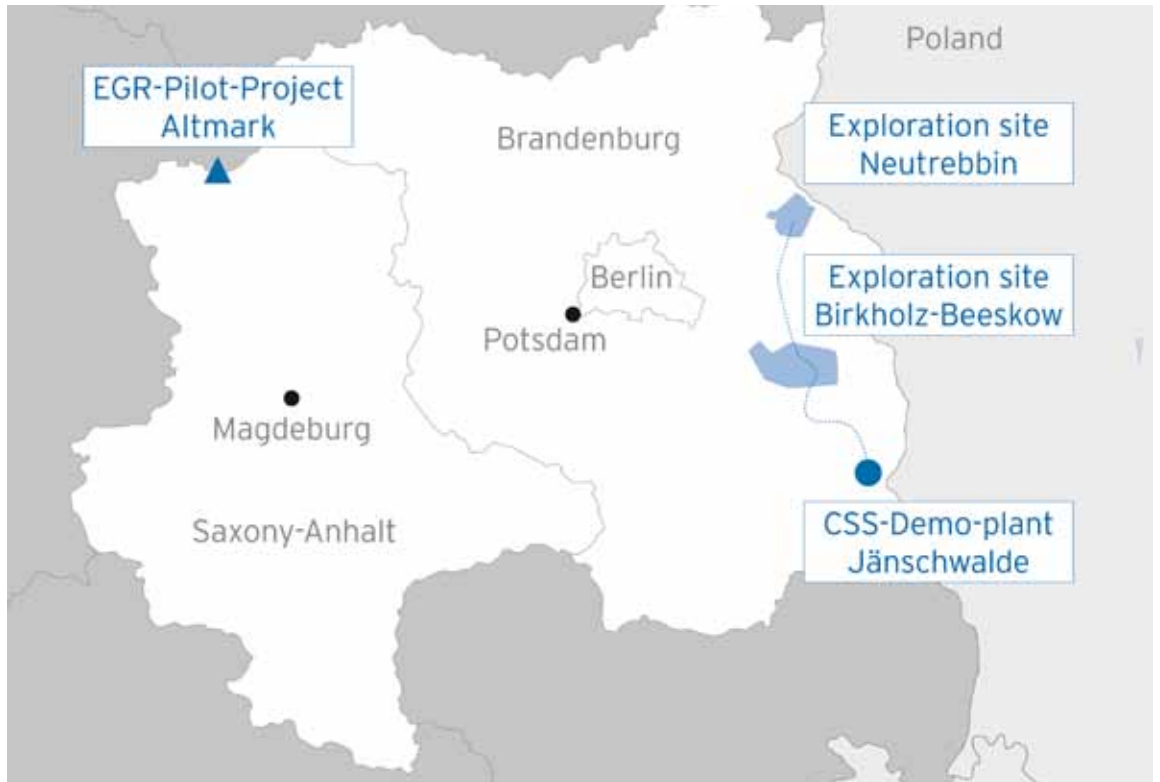
Performing a FEED study requires a number of input data and prerequisites that need to be well thought-out; otherwise the results will be too general and risk being insignificant. The prerequisites for the study in question have been taken directly from Vattenfall's demonstration project in Jämschwalde with the proposed pipeline route to the Birkholz structure 53 kilometres away.

## European competence in CO<sub>2</sub> pipeline transport

The pipeline transport of CO<sub>2</sub> is a quite common operation in other parts of the world, especially in North America where CO<sub>2</sub> is used for EOR, Enhanced Oil Recovery. In EOR, media such as water and/or CO<sub>2</sub> are used to increase the pressure in the oil fields, dissolve the remaining oil and thus facilitate further oil production.

Hands-on experience from CO<sub>2</sub> pipelines in Europe is rare, but the Hungarian oil and gas engineering company has worked for the Hungarian oil and gas company MOL and has designed and constructed CO<sub>2</sub> pipelines for EOR purposes, and they won the bid to perform the FEED study for Vattenfall.

Results from the study are expected during the spring of 2011.



Proposed route for pipelines from the CCS Demonstration plant at Jänschwalde to Birkholz and Neutrebbin. The distance to Birkholz is 53 km and to Neutrebbin 100 km.

## VATTENFALL'S VIEW ON CO<sub>2</sub> PIPELINE TRANSPORT ESTABLISHED

If CCS is to be implemented on a large scale, vast quantities of CO<sub>2</sub> will have to be transported from the capture facility to underground storage locations onshore as well as offshore. The primary means of transport for this will be pipelines for dense phase CO<sub>2</sub>.

Industrial experience of the pipeline transport of dense phase CO<sub>2</sub> for CCS is limited and existing standards for natural gas pipelines are not fully applicable for CO<sub>2</sub> in a dense phase. In 2008, the Norwegian organisation Det Norske Veritas therefore launched a well-supported Joint Industry

Project, JIP CO<sub>2</sub>PIPETRANS, with the objective of developing a recommended practice for the transmission of dense phase CO<sub>2</sub> in onshore and submarine pipelines. The aim of the recommended practice was to complement existing standards with CO<sub>2</sub>-specific guidance on the issues and con-

siderations associated with the design and operation of dense phase CO<sub>2</sub> pipelines.

Intended users of the recommended practice document are CCS project developers, pipeline engineering and construction companies, pipeline operating companies, authorities and certification companies.

#### **CO2PIPETRANS continues**

The resulting recommended practice was launched in May 2010. During execution of the first phase of CO2PIPETRANS, a number of significant gaps in knowledge were identified that ought to be filled to enable large-scale CO<sub>2</sub> pipeline development. Together with 14 partners, Vattenfall has signed the consortia agreement for a second phase of CO2PIPETRANS. The main objective of the second phase is to close the knowledge gaps identified in the first phase of the project.

One of the crucial areas that will be covered in phase 2 of the JIP is the controlled release of dense phase CO<sub>2</sub>, in order to gain data for the validation of existing modelling work. Another focal point is to investigate more closely how a pipeline reacts if damaged through a fracture. There is a risk that a damaged pipeline will develop a so-called running ductile fracture, which can be described as a very rapid propagating crack that "un-zips" a pipeline along its length. The project will focus on how this kind of damage can be prevented and, if it nevertheless does occur, how to minimise the consequences. A third objective of the project is to take a closer look at material issues and the risk of corrosion.

#### **Vattenfall view established**

The interest in JIP CO2PIPETRANS and the resulting recommended practice has been extensive and the importance of such guidelines is recognised. This view is also supported in an internal Vattenfall study performed in 2010, which aimed to arrive at a Vattenfall view on the current status of safety and risk analysis for CO<sub>2</sub> pipelines for CCS. The guideline developed in the first phase of CO2PIPETRANS was one of the numerous external reports that were reviewed. Vattenfall's view on the topic is based on publicly-available knowledge and industrial experience, ranging from selecting preferred design options to recommendations on the engineering design and risk assessment, but also in-house experience gained in the now shelved CCS demonstration project in Northern Denmark.

Not only did the main findings and recommendations of the internal study emphasize the importance of DNV's recommended practice, it also highlighted the importance of large CO<sub>2</sub> release tests and model validations like those that will be performed in the second phase of the JIP. Accurate modelling of dense phase CO<sub>2</sub> both within the pipeline system and during release situations is essential for pipeline design and operations. It is also central for gaining stakeholder acceptance in, for example, permit processes and public consultations. Today, very few models, if any, exist that have been validated for modelling dense phase CO<sub>2</sub> on the scale applicable for CCS.

CO2PIPETRANS phase 2 will result in an updated version of the recommended practice by the end of 2012.

# GROUNDWATER MODEL IN VEDSTED

Monitoring of the storage complex and its surrounding environment is an essential part of the EU Directive on the Geological Storage of CO<sub>2</sub>. It is crucial that we assess potential effects and monitor the storage area for any indications of impacts. To be able to detect any impacts on the surrounding environment, we need to establish the natural levels and variations of CO<sub>2</sub> and other relevant parameters in the storage area. In line with this, Vattenfall is working to develop a groundwater model for the Vedsted site in Denmark.

## **Interface between groundwater and brine**

For drinking water, which is directly mentioned in the EU directive, the characterisation of chemical components is necessary along with studies of the groundwater flow and the interface between the sweet drinking water and the saline brine below. A groundwater model that simulates the groundwater flow and demonstrates that the stored CO<sub>2</sub> does not affect the groundwater in any way is therefore under construction for the Vedsted site. The static geological model that describes the layers of sand, clay and chalk in which the ground water flows is now being finalised. The next step is to perform dynamic simulations of the flow, for which the first data on salinity and flow in the drainage system is being collected.

The project has earlier described a conceptual geological model that defined the limits of the model, the layers necessary to define the geological variation in the area and the data available for the model.

## **Shallow water table**

The water table in the Vedsted area is often found to be very shallow due to the topography, and it is therefore expected that the interface to the saline brine below will also be shallow. Geochemical data are primarily found in wells, situated in the topographical higher areas where larger amounts

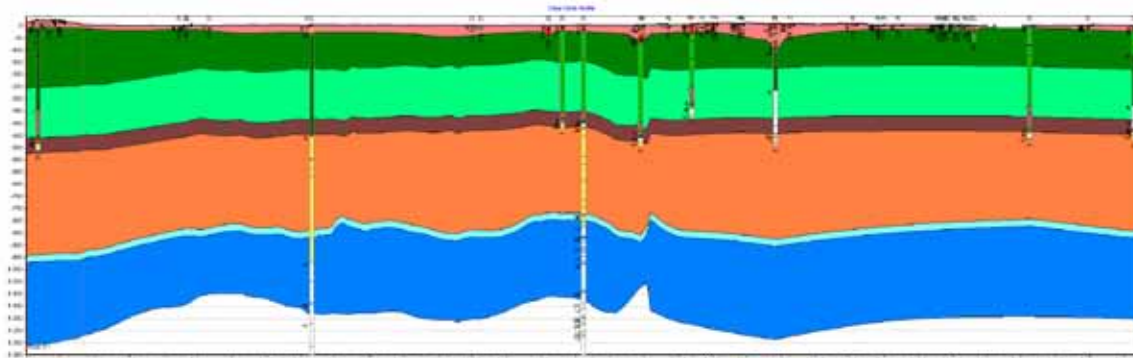
of sweet water are found. For some of these wells a clear development towards higher salinity can be documented from the historical data collected for the groundwater model. This development is probably due to exploitation of the sweet water reserve that is above the capacity of the reservoir. It is extremely important to gather such information before the injection of CO<sub>2</sub> starts in order to document that increasing salinity is not caused by pressure from the storage reservoir.

In order to continue moving the project towards a dynamic groundwater model, the availability of dynamic data, which must be collected locally, is crucial. Measurements of salinity and flow in the drainage system are planned for 2011.

## **Model based on historic data**

The groundwater model will be based on historic data and some newer dynamic data. It will be used for research-based modelling of possible pressure impact on the saline brine-sweet water interface. However, it will not work as a baseline for future monitoring of CO<sub>2</sub> levels and pressure impact, since no systematic measurements have been taken. In the important sweet water wells, analyses have been made at as much as 11-year intervals, which makes it impossible to map seasonal variations. Only a few analyses focus on salinity, therefore

The figure shows a transect through the groundwater model for Vedsted. The shallow sands and clays are shown in orange, the green colours represent the chalk and the deeper orange and blue the clayey deposits separated by a thin sandy layer in light blue.



data from areas with severe salinity problems are very old, very irregular and very sparse.

#### **Baseline data needed as well**

Ahead of CO<sub>2</sub> injection, a systematic baseline must be planned as a part of the monitoring plan in

order to fulfil the requirements in the EU storage directive. A study by CO2GeoNet (2009) recommended measurements four times a year for the start-up of a baseline for groundwater.

The flat landscape surrounding the Danish Nordjyllandsværket could be ideal for storage of CO<sub>2</sub>. Although the plans for a CCS demonstration plant at the site have been shelved, it is a continued strategic interest to maintain the exploration licence of the Vedsted site.



# POTENTIAL ENVIRONMENTAL IMPACTS OF CCS

When considering alternatives for the capture, transport and storage of CO<sub>2</sub>, environmental aspects are among the most important factors. The main expected environmental effect of introducing CCS to fossil-fuelled power generation is significantly reduced emissions of greenhouse gases.

Since CCS is a new technology that is still under development, there will be new environmental challenges that need to be identified and managed. A study on the environmental effects relating to the capture, transport and storage of CO<sub>2</sub> was conducted in 2010 with the aim of documenting generic information and significant aspects that should be taken into account.

At Vattenfall, we are continuously working to increase our knowledge on environmental impacts in the field of CCS. This is done through the initiation of our own research activities as well as through participation in international research and joint industry projects. The focus of this study was to summarise available knowledge and to integrate recent research results on environmental impacts.

## **Increased resource consumption**

Introducing CO<sub>2</sub> capture for coal-based power generation generally increases internal power consumption compared to plants without CO<sub>2</sub> capture. This will lead to increased fuel consumption and higher environmental pressure from upstream processes. Larger amounts of chemicals, waste and by-products will need to be handled per generated kWh compared to conventional power plants. The water consumption of the power plant is also expected to increase, which is a question that will have to be addressed when planning for CCS, to secure sustainability.

If new capture chemicals are used, trade-off effects may occur where some new pollutants are introduced to the system and some traditional

emissions are removed in the processes. The fate of pollutants and trace elements may change, shifting from emissions to air into other streams, such as waste water. A minor slip of solvents from postcombustion CO<sub>2</sub> capture is expected to air. Amine-based solvents are highly water soluble, and according to suppliers, the slip can be reduced to very low levels (a few ppm or less). Ultimately, all emissions will be controlled by the environmental permit of an installation.

## **Pipeline better than ship**

Large-scale transport options are ship and pipeline; the means of transport used will depend on the quantity of CO<sub>2</sub> to be transported, the terrain and the distance between the capture plant and the injection site. The technology and potential environmental effects that relate to CO<sub>2</sub> transport are considered to be known to a great extent, from existing CO<sub>2</sub> pipelines used in Enhanced Oil Recovery operations and analogue activities such as the transport of natural gas. A well-planned CO<sub>2</sub>-pipeline transport system is expected to have a low impact on the environment, and impacts are expected to mainly relate to construction and decommissioning, together with some controlled fugitive emissions. Results from an internal life-cycle assessment have shown that pipeline transport has a better environmental performance than ship transport, due to the potential for high SO<sub>2</sub> emissions from the ship.

## **Avoid and minimise risks**

The environmental assessment of CO<sub>2</sub> storage is highly site-specific. It is necessary to predict

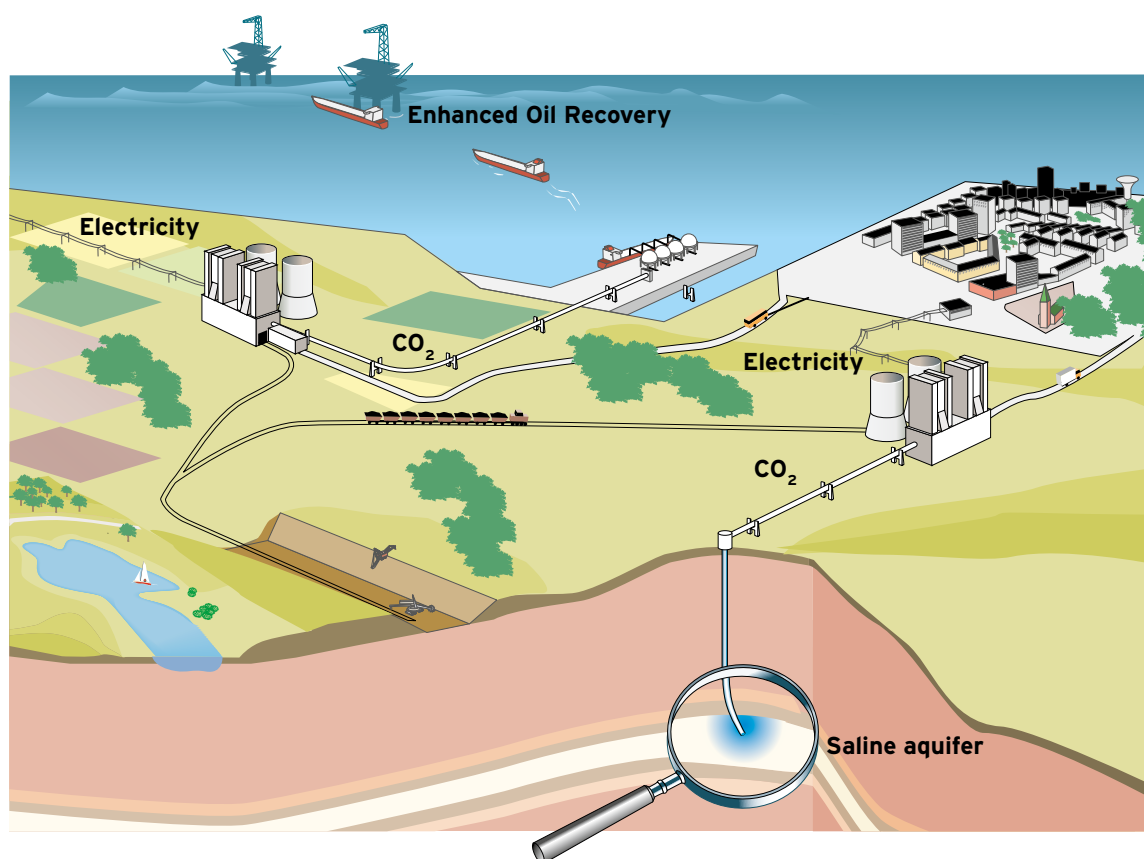
potential environmental consequences during the construction, operation and after-closure phases. Potentially critical issues and environmental risks need to be identified, including the consequences of a leakage of CO<sub>2</sub> and the potential impacts of displacement of formation fluids, so that precautionary measures can be taken and risks minimised and avoided.

As CCS is a technology under development, the main knowledge gap consists of lack of data from actual applications. When assessing risk scenarios, the impacts of elevated CO<sub>2</sub> levels in surface water, wetlands and groundwater are areas that require further studies. Vattenfall is currently engaged in research in the field of impacts on groundwater and surface water, through involvement in local projects and larger EC projects (e.g. RISCs). The

potential impact on groundwater quality from the leakage of CO<sub>2</sub> or the potential intrusion of brine is an important factor to take into consideration when describing risk scenarios for future CCS permit applications.

### CO<sub>2</sub> emissions drastically reduced

The world of today is largely dependent on CO<sub>2</sub>-emitting fossil fuels, and changing to a more sustainable energy system will take time. The main objective of capturing and storing CO<sub>2</sub> from power plants is to keep it from reaching the atmosphere where it would otherwise contribute to the enhanced greenhouse gas effect and climate change. When considering the environmental consequences and risks of CO<sub>2</sub> storage, it has to be seen in perspective of the greater consequences and risks associated with the continued emissions of CO<sub>2</sub>.



All parts of the CCS chain involve impact on the environment. However, the largest impact of CCS is the drastically-reduced emissions of CO<sub>2</sub>.

# OUTLOOK 2011

From the start of year 2011 and for a few years onwards, Vattenfall will undergo a consolidation phase in reaction to a change in the market situation. This will be accompanied by a major reorganisation of our business and divisions and a critical review of strategic priorities. For the R&D area this means improving the focus on those projects where the benefits to our business goals are clear.

CCS continues to be such an important element of our future plans for large-scale electricity generation and CCS R&D efforts will be concentrated on those areas that directly support our demonstration projects and the first generation commercial-scale plants thereafter, i.e. Postcombustion, Precombustion and Oxyfuel. The corporate CCS R&D unit has been expanded to further improve programme management, local integration and knowledge transfer within the Asset Development Division.

## **CO<sub>2</sub> Capture R&D**

For 2011, some areas have been identified as being especially important within capture R&D.

Our understanding of Oxyfuel combustion characteristics and the implications this has on boiler design will be further improved. This will be done mainly by the work performed at the pilot plant in Schwarze Pumpe, but also in cooperation with different technology suppliers, universities and research institutes.

Mass balances over the different components in the Oxyfuel process will be validated. The cost benefits of different concepts for the removal of trace elements in the process will be mapped.

Our existing knowledge on material issues in Oxyfuel and Postcombustion processes will be refined and validated. This will mainly be done through experiments in the pilot plants that we are involved in.

Regarding Precombustion capture; the test programme will be started, at the CO<sub>2</sub> Catch-up pilot plant, with the aim of verifying the technology performance and validation of the process models.

Control and operation strategies for the different capture processes will be developed using validated dynamic simulation tools.

Technology and process parameters for the highest HSE (Health, Safety and Environmental) performance standards will be identified.

Alternative capture processes, which could lead to significant efficiency improvements, will be reviewed.

## **R&D on Transport & Storage of CO<sub>2</sub>**

Some activities are particularly important for 2011. The Transport & Storage Programme will be assessed in the light of the directions outlined in Vattenfall's recent strategic realignment. This assessment should aim to increase the focus of the related R&D activities on Vattenfall's business objectives and the needs of the corporate CCS demonstration projects.

Involvement in pilot-scale CO<sub>2</sub> test injection storage endeavours will be established.

Open questions relating to CO<sub>2</sub> storage operations will be addressed. This work will aim to optimise storage performance.

CCS is a way of bridging over to other, renewable technologies for power generation in the future energy system.



As a result of industrial cooperation projects, in which Vattenfall has played an important role, guidelines and working procedures are available for CO<sub>2</sub> transport and storage. The in-house implementation of these guidelines and procedures is prioritised.

Greater efforts will be made to improve the transfer of knowledge into Vattenfall's CCS demonstration projects.

#### **Environmental R&D**

Health, safety and environment (HSE) issues will continue to play an essential role in Vattenfall's programme for CCS R&D. The focus in 2011 will be on the following topics.

In 2007, 2008 and 2009 life cycle analyses (LCA) were produced for the total CCS chain, that is capture, transport and storage, and these results will be updated. The results are based on general data, not from specific plants or sites.

Further R&D activities to improve our knowledge of the HSE risks connected to the use of amine-based solvents for Postcombustion CO<sub>2</sub> capture will be

conducted. Focal areas for research include degradation mechanisms in the Postcombustion process, analysis of emissions and waste streams, mitigation methods, dispersion modelling, environmental fate of emissions, toxicology, natural background levels and limit levels.

A monitoring plan for the Birkholz storage site in Germany will be conducted. Risk assessment, monitoring technology and methods, the development of a groundwater

model for the area and the planning of baseline studies will be covered.

The final part of the development of a groundwater model for the Vedsted storage site in Denmark will be performed. A groundwater model is an important component when developing a monitoring plan for a storage site.

Vattenfall's internal knowledge of mitigation and remediation methods to minimise the potential negative environmental impact of CO<sub>2</sub> leakage or the displacement of formation water will be improved. These methods will be coupled with a monitoring plan to ensure that the company is prepared to address any unexpected events with a potentially negative environmental impact.

Our understanding of potential impacts on ecosystems from exposure to CO<sub>2</sub> leakage will be improved.

Vattenfall's Strategic Environmental Assessment of CCS and our CCS HSE risk assessment will be updated.

#### **New organisation 2011**

As mentioned earlier, Vattenfall has undergone a major reorganisation, with the new organisation coming into operation on 1 January 2011. This has affected the CCS R&D Program, which has also reorganised its structure. Following this reorganisation, CCS R&D is placed under Asset Development (Huib Morelisse) and R&D Projects (Karl Bergman) with, as before, Göran Lindgren as Head of CCS R&D.

The structure has also changed within CCS R&D, which now includes an organisation for coordinating all the parts of the program. The scope is largely the same as before, but has expanded with the Dutch CCS activities entering the program with an R&D project and a pilot plant in Buggenum, which will increase our knowledge concerning Pre-combustion capture.

**Göran Lindgren** - Head of CCS R&D  
**Moritz Köpcke** - R&D Capture Germany  
**Kay Damen** - R&D Capture Netherlands  
**Thomas Schulte** - R&D Storage & Transport  
**Uwe Burchardt** - Oxyfuel Pilot Plant in Schwarze Pumpe  
**Stephanie Tappe** - Alternative CO<sub>2</sub> Purification Pilot Plant in Schwarze Pumpe  
**Radoslaw Gnutek** - Precombustion Pilot Plant in Buggenum  
**Niels Peter Christensen** - Storage & Transport Strategies  
**Staffan Görtz** - Communication, Acceptance and HSE

#### **SUPPORTING:**

**Ellen Corke** - Project Controller  
**Magnus Petterson** - HSE Projects

## ONGOING PROJECTS IN 2010

A large number of projects were initiated and finalized during 2010. Below is a list that presents all the projects that were ongoing in 2010. Most of them were also finalized during the year, but some of them are still ongoing. Almost all of the projects are summarized in a report or a memo. Some of the projects have also been presented at seminars or conferences.

Project name	Project Leader
<b>CAPTURE</b>	<b>COORDINATED BY MARIE ANHEDEN</b>
Removal of NO <sub>x</sub> and SO <sub>x</sub> i CO <sub>2</sub> compression plant	Jinying Yan
Dynamic simulation of oxyfuel plant phase 2	Erik Ramström
Benchmarking postcombustion	Maria Jonsson
Relocation of NO <sub>x</sub> in CO <sub>2</sub> compression plant	Maria Jonsson
Oxyfuel concept study	Karin Ifwer
Oxyfuel CFB development and validation	Nicklas Simonsson
Vattenfall OxySO <sub>x</sub> project	Jinying Yan
Biofuels in pilot plant	Olle Jidinger
Lignite ash minerology	Holger Ecke
Degradation in oxyfuel by carburisation	Bengt Hildenwall
Postcombustion dynamics phase 2	Richard Faber
Knowledge building on CO <sub>2</sub> compressors	Jan Ukonsaari
Pilot simulation cont CFD	Karin Eriksson
Project management, REI	Karin Eriksson
Air Products CO <sub>2</sub> miniplant, phase 3	Marie Anheden
GRE dryer evaluation phase 2	Maria Jonsson
Interface development DTU	Richard Faber
Selection/Evaluation of high dust SCR catalysts for Oxyfuel process	Nader Padban
Knowledge buildup of solid sorbents	Benny Fillman
Amine Measurements, phase 1	Linda Nylén
Absorption of SO <sub>x</sub> and NO <sub>x</sub> in the CO <sub>2</sub> compression unit	Linda Nylén
Cooperation with Chalmers on CLC and CLOU	Jens Wolf
Amine emissions with flue gases, phase 1	Marie Anheden
Amine measurements phase 2	Linda Nylén

Project name	Project Leader
Improvements of ASU for oxyfuel applications, phase 1	Nicklas Simonsson
Radiation modelling	Karin Eriksson
Evaluation of CCS plants with co-combustion of solid biomass	Karin Ifwer
Oxyfuel FGD chemical modelling prestudy	Benjamin Faulhaber
Capture R&D Seminar	Ida Mann
Hitachi burner CFD modelling	Jan Eriksson
Oxyfuel Concept Study 2010 phase 2	Jonas Alin
Relocation of NO <sub>x</sub> in the oxyfuel process, validation and optimisation	Nader Padban
Materials and Corrosion for Postcombustion Capture	Henrik Sieurin
Oxyfuel Process Development through Implementation of Membrane Technology	Nicklas Simonsson
Oxyfuel Process Development through ASU and CPU Improvement and Integration	Nicklas Simonsson
Oxyfuel knowledge transfer	Marie Anheden
Oxyfuel Dynamics, phase 3	Jonas Funkquist
Chemical looping combustion, reaction modelling Eclair	Jens Wolf
Chemical looping combustion, reactor modelling Chalmers	Jens Wolf
Validation of SCR for Oxyfuel	Raziyeh Khodayari
Collaboration with Chalmers on So <sub>x</sub> and No <sub>x</sub> in the CO <sub>2</sub> compression train	Raziyeh Khodayari/ Linda Nylén
AirBoiler Model Validation	Jonas Funkquist
OxyVal	Karin Eriksson
Epsilon heat transfer models	Erik Ramström
Reclaiming technology review	Marie Anheden
<b>STORAGE &amp; TRANSPORT</b>	<b>COORDINATED BY CHRISTIAN BERNSTONE &amp; JENNY-ANN NILSSON</b>
Best practice on CO <sub>2</sub> pipeline transportation	Jenny-Ann Nilsson
R&D Support to maintain the Vedsted exploration licence 2010	Finn Dalhoff, Lone Klinkeby
Conceptual design feed study of a CO <sub>2</sub> pipeline 2010	Jenny-Ann Nilsson
Corrosion on CO <sub>2</sub> pipeline 2010	Jenny-Ann Nilsson
Alternative drilling technologies for CO <sub>2</sub> storage projects	Finn Dalhoff
Dev. of a VF internal CO <sub>2</sub> storage site database	Finn Dalhoff
Research on the Birkholz and Vedsted reservoir models 2010	Lone Klinkeby
VF CO <sub>2</sub> Storage Strategy 2010	Finn Dalhoff
Injection flow model research - Birkholz structure	Lone Klinkeby

Project name	Project Leader
Investigation of current methods for pipeline risk assessment	Jenny-Ann Nilsson
Implementation of the CO2QUALSTORE guideline in VF	Finn Dalhoff
Baseline Monitoring Plan for the Birkholz storage site, Phase 1	Lone Klinkeby
CO <sub>2</sub> Transport Dynamics Paper for GHGT-10	Jenny-Ann Nilsson
Risk Analysis Presentation on GHGT-10	Jenny-Ann Nilsson
A CO2WELLS JIP Satellite Project: Case Study Vedsted 1 Well	Finn Dalhoff
Developing the EUDP project application "The value chain of CCS in combination with geothermal energy"	Finn Dalhoff
Vedsted levelling baseline using satellite based monitoring techniques	Ann Troelsgaard Sorensen
AQUA-DK (JIP)	Ann Troelsgaard Sorensen
SKAGERAKK III (JIP)	Christian Bernstone
CO2PIPETRANS II (JIP)	Christian Bernstone
CO2WELLS (JIP)	Finn Dalhoff
LEAKEPREV (JIP)	Christian Bernstone
OXYGAS III (JIP)	Christian Bernstone
MOPA (National R&D Programme)	Christian Bernstone
COORAL (National R&D Programme)	Christian Bernstone
CATASTER (National R&D Programme)	Christian Bernstone
CLEAN (National R&D Programme)	Christian Bernstone
CO2DYNAMICS (National R&D Programme)	Christian Bernstone
CO2MAN (National R&D Programme)	Christian Bernstone
CO <sub>2</sub> -GS (National R&D Programme)	Christian Bernstone
<b>ENVIRONMENT</b>	<b>COORDINATED BY MAGNUS PETERSSON &amp; SARA MCGOWAN</b>
Groundwater study step II - Vedsted	Lone Klinkby
HSE Capture - Amine solvent roadmap and oxyfuel activities	Magnus Pettersson
LCA 2010	Mikael Strand
SEA 2010 and environmental impacts	Sara McGowan
EIA - Experiences from existing CCS projects	Magnus Pettersson, Sara McGowan
ADA (JIP)	Magnus Pettersson
ExSIRA (JIP)	Magnus Pettersson
Testing at Esbjerg (JIP)	Ole Biede

Project name	Project Leader
<b>GENERAL</b>	
CO <sub>2</sub> Capture, Storage & Transport - Benchmarking 2010	Marie Anheden, Christian Bernstone & Jenny-Ann Nilsson
Elforsk CCS-program 2010	Christian Bernstone
ZEP and other european CCS R&D issues	Clas Ekström
Research on CCS scenarios for VA Poland, phase 1	Tiina Tarvis
Research on CCS scenarios for VA Poland Warsaw Scenario Development	Tiina Tarvis, Leif Liinanki & Dean McGowan
<b>PILOT PLANTS</b>	
OxPP	Olle Jidinger
OxyCoal	Stina Rydberg & Jan Eriksson
CCPilot100+	Moritz Köpcke & Jonas Alin
<b>EU-PROJECTS</b>	
CESAR (2008-2011) stands for CO <sub>2</sub> Enhanced Separation and Recovery; European project funded under the 7th Framework Programme	Jonas Alin
Eclair (2008-2012) Emission free Chemical Looping Coal Combustion Process; European project funded under the 7th Framework Programme	Marie Anheden
OxyCorr (2009-2012) Boiler corrosion under oxyfuel conditions; EU collaboration project supported by Research Fund for Coal and Steel	Alexander Gerhardt
iCAP (2009-2013) Inovative Capture Technologies; European project funded under the 7th Framework Programme	Jonas Alin
CO2REMOVE (2006-2011); European project funded under the 6th Framework Programme	Christian Bernstone
ECCO (2008-2011) European Value Chain for CO <sub>2</sub> ; European project funded under the 7th Framework Programme	Christian Bernstone
CO2EUROPIPE (2009-2011) Towards a transport infrastructure for large-scale CCS in Europe; European project funded under the 7th Framework Programme	Christian Bernstone
RISCS (2010-2013) Research into Impacts and Safety in CO <sub>2</sub> Storage; European project funded under the 7th Framework Programme	Sara McGowan & Christian Bernstone
SITECHAR (2010-2012) Characterisation of European CO <sub>2</sub> Storage; European project funded under the 7th Framework Programme	Christian Bernstone

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