BRIDGING TO THE FUTURE

Newsletter on Carbon Capture & Storage at Vattenfall | No. 17, December 2010

Additional pilot plant in Schwarze Pumpe

The CCS demo project in Jänschwalde is moving ahead

VATTENFALL

About Carbon Capture & Storage at Vattenfall

Climate change is one of the greatest environmental challenges of our time. Vattenfall's ambition is to reduce its absolute CO_2 emissions from 90 million* tonnes to 65 million tonnes by 2020. Carbon Capture and Storage, CCS, is one method to achieve this, and for this reason we initiated our efforts on CCS in 2001. The aim is to make commercial CCS concepts available in 2020.

CCS is a way of bridging over to other, renewable technologies for power generation in the future energy system. This is why we call our newsletter "Bridging to the Future".

Vattenfall is Europe's fifth largest generator of electricity and the largest generator of heat. We currently have operations in Denmark, Finland, Germany, the United Kingdom, Poland, the Netherlands and Sweden. Vattenfall will create a strong and diversified European energy portfolio with sustainable and increased profits, significant growth and will be among the leaders in developing environmentally sustainable energy production.

CCS at Vattenfall in brief:

• The **Jänschwalde Demonstration** Project has been started in Germany. Different storage options are currently being investigated.
• There are plans for a large-scale precombustion CCS project at the Magnum plant in Eemshaven in the Netherlands.
• Nordjyllandsværket in Denmark is a possible "early commercial" power plant. The CO_2 would be transported in a 30-kilometre pipeline to the Vedsted underground structure for storage.
• **R&D** to support the large scale projects is performed in all parts of the CCS chain; Capture, Transport and Storage. Most well known is the **Oxyfuel Pilot Plant** in Schwarze Pumpe in Germany that has been in operation since 2008. At the coal gasification plant in Buggenum, the Netherlands, a Precombustion CO_2 capture pilot plant is taken into operation.

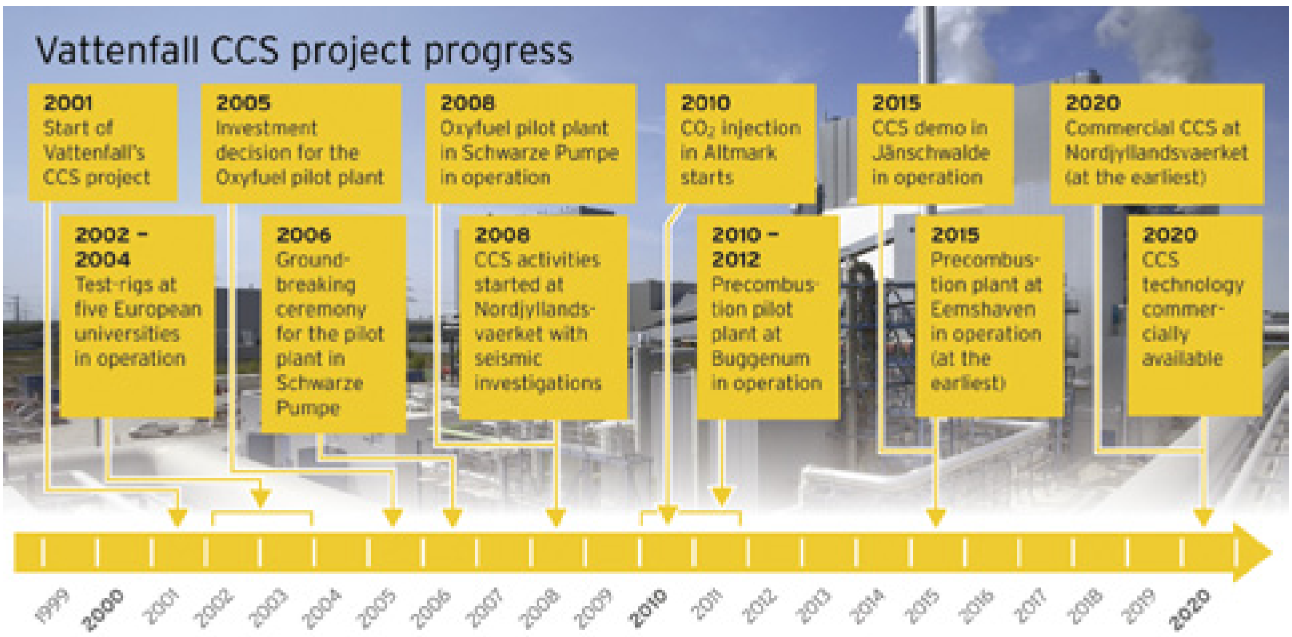
Environmental issues are also covered by CCS R&D activities. Vattenfall is an active partner in a number of EU projects.

Bridging to the Future

Bridging to the Future is the CCS project's newsletter and it is circulated three times a year. The newsletter's ambition is to give a comprehensive picture of all parts of the projects and keep the readers up to date on advances in research. All the editions can be found on the project website www.vattenfall.com/ccs. There you can also subscribe to future issues by e-mail. If you have any comments or questions about the newsletter, please contact the editor Kristina Leufstedt at: kristina.leufstedt@vattenfall.com.

If you have questions about the project, please contact the project group at: ccs@vattenfall.com
Göran Lindgren is R&D Programme Manager CCS.
Kristina Leufstedt is editor and Staffan Görtz is legally responsible for this newsletter.

*2009



CCS – one of Vattenfall's options for reducing its CO_2 exposure

In October 2010, Vattenfall went public with its new strategic directions. One of the focus areas is still reduction of the company's CO_2 exposure – short term as well as long term. In the long term, CCS still looks like the most promising of the options when it comes to reducing global CO_2 emissions at scale to affordable costs.

In the meanwhile, Vattenfall moves on with its projects on developing and demonstrating CCS. The Oxyfuel pilot plant at Schwarze Pumpe continues to deliver good results, as do the other pilot projects in which we are involved.

On 10 November, the European Commission published a call for proposals regarding the NER300 funding of CCS demonstration plants. We welcome this. Financial support is necessary if we are to be able to take the final step; full-scale demonstration of the whole CCS chain - capture, transport and storage - before commercial deployment.

Göran Lindgren
CCS R&D Programme Manager

Contents

No. 17, December 2010

Cover: Additional pilot plant in Schwarze Pumpe. Photographer: Uwe Dobrig

Additional pilot plant in Schwarze Pumpe

Visitors to Vattenfall's Oxyfuel pilot plant at Schwarze Pumpe may notice a new addition to the pilot plant the next time they visit. Air Products has been busy working with Vattenfall over the last couple of years to realise the ambition of building the world's first complete pilot of the technology designed to purify the raw CO_2 from an oxycoal system. A new unit has been placed along the west side of the Oxyfuel pilot plant and utilises a slip stream of the flue gases, taken off just after the particle removal unit.

The technology uses three concepts that have been in development for a number of years and will together lead to an optimised, low-cost, high-efficiency Oxyfuel CO_2 capture plant. The new unit comes after the study work that Air Products carried out for Vattenfall that was reported in the September 2007 edition of Bridging to the Future.

Separation at low temperature

The core of the system is the low-temperature partial condensation process used to purify the raw CO_2 once it has been compressed and dried. The purpose of this process is to remove the atmospheric gases nitrogen, oxygen and argon from the CO_2. The process is referred to as "partial condensation" since not all of the feed gas will condense as the stream is cooled to near CO_2-solidification temperatures. The argon, nitrogen and oxygen in the feed stream will mostly stay in the vapour phase and be separated as an inert vent stream. Some though will remain dissolved in the CO_2, but these impurities can also be removed using a distillation column integrated into the partial condensation process, producing a stream with greater than 99% CO_2 purity.

However, the key to the efficiency of this low-temperature process is the refrigerant. Rather than using a conventional ammonia cycle, here the CO_2 product itself is used to cool the raw CO_2, making this the first Oxyfuel CO_2 purification demonstration plant to use this auto-refrigerated concept which will deliver significant power-reduction savings when applied to commercial-scale plants.

Inherent removal of SOx and NOx

One of the most exciting parts of the new unit is the process by which the raw CO_2 is delivered to the low temperature process using a concept that Air Products calls the sour compression process, which efficiently removes SOx and NOx from the feed CO_2. During compression to 30 bar, any SOx and NOx in the raw CO_2 will react to form acid. Now, this could be bad news if this happens unexpectedly, or in the wrong place, but since Air Products discovered this concept in 2005 they have utilised 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 SOx and NOx from the raw CO_2 stream, potentially saving in more expensive upstream control options and minimizing potential downstream corrosion. Air Products has developed the sour compression process in laboratory-scale experiments with Imperial College and, more recently, as part of a DOE cooperative agreement.

Membrane to recover CO_2 and O_2

The next step addresses the inert stream that leaves the low temperature process and how to maximise recovery from this stream. The composition of this stream is determined by the vapour phase equilibrium at the cold end of the process, and in this stream there will be some CO_2. The amount of CO_2 leaving through this vent stream would then determine how much CO_2 can be captured by the process. What we need is a way to capture the CO_2 in the vent stream as well – and that is the third aspect of the new unit currently nearing completion in Schwarze Pumpe. Air Products has installed a series of PRISM® membrane modules that will demonstrate the recovery of CO_2 from the vent stream so that on a commercial plant this CO_2 can be recovered back to the process. The bonus in this process is that whilst this membrane is recovering CO_2 it is also recovering oxygen, which, once recovered to the boiler with the co-captured 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.

Soon in operation

So, in a matter of weeks, Air Products will start taking raw CO_2 from the Vattenfall Oxyfuel pilot plant to feed to the new unit. The flue gas stream will correspond to roughly 1 MW^{th}, or slightly more than 3% of the flue gas flow from the boiler. After it has passed the new unit, the CO_2 stream will be re-fed to the flue gas flow of the Oxyfuel pilot plant and end up in the CO_2 tanks on site. Vince White, from Air Products about the collaboration with Vattenfall: "We are pleased to be approaching this point where our Oxyfuel Purification technology can be proven on a scale that will allow future demonstration plants to be designed using the inherent advantages of our system. Through our collaboration with Vattenfall we have been able to accelerate the development of this technology which will allow the fundamental advantages of Oxyfuel over other CO_2 capture technologies to be exploited."

The new unit, which will be owned and operated by Vattenfall, will allow important data to be collected to assist in the design and optimisation of the next step: a demonstration plant. As announced in March 2009, Air Products and Vattenfall will cooperate under a joint research and development agreement to direct the research of the new unit as both companies improve their fundamental knowledge of the Oxyfuel CO_2 purification and compression process and strive to optimise this important element of enabling Oxyfuel CO_2 capture from coal combustion.

Gunnar Langer, Vattenfall and Robert Haak, Construction supervisor from Air Products, in front of the new unit installed at Schwarze Pumpe. The whole new unit can be seen on the cover

PHOTOGRAPHER: UWE DOBRIG

Two years of continuous testing in Schwarze Pumpe

Inaugurated in September 2008, the Oxyfuel pilot plant in Schwarze Pumpe has now been running for more than 9 300 hours and has produced more than 4 300 tons of liquid carbon dioxide. According to the project team, the findings from this phase show that the Oxyfuel process works and can be scaled up to the next phase of a demonstration plant.

Different tests and measurements have taken place during the last two years. Starting with the installation of different types of burners for the combustion chambers and tests on combustion temperature, the most recent milestone has been the assembly of an alternative CO_2 treatment by the American company Air Products (see article beginning on previous page) that should contribute to a deeper understanding of CO_2 compression and purification in the oxyfuel process. In addition, the purity of the produced CO_2, which lies at 99.7%, is definitely something to be proud of.

Facing the challenges

There are still challenges to be overcome, although they are mainly not of a technological nature. After two years of operation, we have not been given permission for geological storage of the CO_2 produced. Instead the liquefied carbon dioxide is released into the atmosphere again at the end of the process chain. We think this is unfortunate, as we spend a lot of effort on captuing it and wish to learn more about transport and storage.

For Vattenfall it is crucial that local authorities, politicians at all levels, the general public, inhabitants in the vicinity of the power plant and a possible storage site feel well informed and get more knowledge about the ongoing activities, as well as on the principles of the CCS technology. We welcome a dialogue about our activities.

Moving ahead – The CCS demonstration project in Jänschwalde plays a leading role in Europe

The European Energy Programme for Recovery (EEPR) has been set up by the European Commission in order to support – amongst others – CCS projects that have proven to be at a mature stage. One of these projects is the planned demonstration plant in Jänschwalde that Vattenfall wants to build from 2011 onwards.

The Jänschwalde demo project has been rated as the most advanced of the six CCS projects the programme supports financially across Europe and will receive EUR 180 million of funding.

Site preparation has started

In Jänschwalde, the site preparation has already started providing space for the new CCS related equipment. The construction site shall be cleared completely by the end of this year. Overall, the capture part of the project is making good progress with 30 Vattenfall employees handling the preparations and planning. One important milestone is also due this year: awarding the contract for the air separation unit is a task that has to be completed in 2010, according to the ambitious project schedule.

Challenges to overcome

Vattenfall is awaiting permission to start exploring the two potential storage sites in Eastern Brandenburg. Presently we are awaiting a legal framework in Germany to be in place before we can make the investment decision. In the meanwhile planning and engineering continues for us to be able to take it into operation by 2015.

European Energy Programme for Recovery

Inauguration Ceremony at Chemical Looping Combustion test facility in Darmstadt

On November 3, a new 1 MWth Chemical Looping Combustion (CLC) pilot plant for the combustion of conventional pulverized coal was officially inaugurated and taken into operation at the Technical University of Darmstadt, Germany. The pilot plant is the first approach to demonstrating the novel CLC principle in a complete auto-thermal reactor system. Some 95 guests were invited to the inauguration ceremony, ranging from politicians to industry partners, and Vattenfall was among them.

In March 2009, the first cornerstone was laid at the CLC pilot plant construction site at the Technical University of Darmstadt in Germany. Construction has been carried out since then and was completed this autumn. Commissioning will continue for the rest of the year and the first tests for the whole reactor system are scheduled to begin in February next year.

Vattenfall works broadly to promote and monitor the development of the CLC technology. Since 2008, Vattenfall has been involved in the EU-funded ECLAIR project, in which the reactor system in Darmstadt is being tested.

ECLAIR - An EU-funded project

The purpose of the EU-funded project ECLAIR (Emission Free Chemical Looping Coal Combustion Process) is to develop CLC for coal combustion with CO_2 capture and to reach an efficiency penalty of less than 3 percentage points and a CO_2 avoidance cost of about €10 - 15 /ton CO_2.

An important milestone on the way to reaching these goals is the construction of the CLC prototype at Darmstadt Technical University. To complement and support the activities in the Darmstadt pilot plant, the ECLAIR project also includes the construction of a smaller test rig at Chalmers Technical University in Gothenburg, Sweden. This test reactor has a thermal capacity of 100kW and, due to its smaller size, a greater flexibility. In addition, less material is needed for experiments; thus, it will be possible to conduct more tests with more different types of oxygen carrier and coal than will be possible in the 1 MW pilot plant.

After the tests made in the ECLAIR project, validation on a larger industrial scale will be needed before the technique can be introduced on full-production scale.

Alstom leads the ECLAIR project. Other partners are Air Liquide, the Spanish research institute CSIC, SINTEF and Vattenfall.

Corinne Beal from Alstom Boiler and also coordinator in the ECLAIR project, names the facility with a bottle of sparkling wine.

The Danish CCS project

At the beginning of 2010, a revised application from Vattenfall was approved by the Danish Energy Agency, allowing the company to investigate the terrain structure at Vedsted in North Jutland for its suitability for storing CO_2. The change with respect to the original application consists primarily in an extended time frame for the preliminary investigations, as the plant at the Nordjylland Power Station has now been changed from a demonstration plant to a commercial one due to be commissioned in 2020 at the earliest.

The forthcoming investigations consist in carrying out flow and conductivity measurements in drainage channels and other watercourses in the area. These measurements will collect data about the natural characteristics of the water at the present time.

The amounts of CO_2 present in the air and groundwater must be recorded before any storage of CO_2 starts. This is the only way of showing that the content remains the same before, during and after storage.

The results of the measurements will contribute to creating a groundwater model. Vattenfall will make this model and the results obtained from it will be available to local municipalities and waterworks.

Postcombustion Pilot Plant enters Construction Phase

The construction of the CCPilot100+ amine scrubbing pilot plant together with the project partners Doosan Power Systems and SSE at Ferrybridge power station in the UK is well under way. The engineering and design work was concluded this autumn and manufacture and construction are making good progress.

The plant will eventually receive a slip stream of flue gases equivalent to 5 MW of electric power from unit 4 of the hard coal-fired block, and will produce 100 tons of carbon dioxide per day. The intermediate process steps and equipment choices have now been designed and engineered by Doosan Power Systems.

The tie-ins for extracting the flue gases and returning the CO_2 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 are finished. Steel support structures are already being assembled on site. All other units and items have been contracted in the UK and abroad and are being manufactured with delivery dates in the winter period.

Vattenfall will learn vital lessons before going large scale

"This is the key project that closes the gap between the intensive years of R&D and our planned 50 MW demonstration plant at the Jänschwalde power plant going on stream in 2015," says Moritz Köpcke, project manager for Vattenfall's team in the collaboration. "Our main role and focus is on testing the equipment performance, the materials, the off-streams and the dynamic operability of the process as a whole. So we are now eagerly awaiting the start of the commissioning period next spring.", concludes Mortiz Köpcke. Vattenfall specialists will be onsite when the two-year period of operation and testing starts next year.

The £21 million project is funded by Doosan, SSE (Scottish and Southern Energy), Vattenfall and the UK Department of Energy and Climate Change (DECC), the Technology Strategy Board and Northern Way.

CCS concept – Not as new as you might think

Vattenfall and many others are interested in carbon capture and storage (CCS), when the technology is used as a means to drastically reduce CO_2 emissions from fossil-fuelled power plants. This application is quite new and to date has not been demonstrated at full scale. However, the different parts of the CCS chain, capture, storage and transportation have been in operation for decades.

The separation of CO_2 has been practiced in the chemical industry for decades. High-purity CO_2 is a standard product with a variety of applications, e.g. in the food and beverage industry, pharmaceuticals, fire extinguishers and for industrial pH control.

CO_2 can be recovered from by-product streams for other industrial activities in, for example, hydrogen plants, ammonia plants, corn-to-ethanol plants and breweries. The CO_2 concentration in these cases is quite high and a typical CO_2 plant typically recovers 200 metric tonnes of CO_2 per day.

Capture and storage

Large-scale CO_2 capture combined with aquifer storage is also performed around the world. A well-known example is the Sleipner gas field off the coast of Norway. Since the start in 1996, around one million tonnes of CO_2 from Statoil's gas field has been captured every year.

The gas is then stored in the Utsira deep saline aquifer 1 000 metres beneath the North Sea. Sophisticated monitoring equipment has not detected any leakage of CO_2. Other examples of projects of CO_2 capture and storage are the Snøhvit project, also in Norway, and In Salah in Algeria.

Transportation

The transportation of CO_2 is also well understood. In the United Stated, a 5 000-kilometre pipeline network has been in operation for over 30 years now. The reason for this is the use on CO_2 for Enhanced Oil Recovery, to increase the mobility of the oil.

The large-scale transportation of CO_2 using ships is not as well known. Today, the commercial transportation of CO_2 at sea is conducted using smaller ships with a payload of about 1 000 m³. However, the ship transport of very large amounts of gas, up to 100 000 m³, can today be accomplished for liquid petroleum and liquid natural gas, LPG and LNG. Experience from transporting LPG and LNG could be used, although there are differences in the vapour-liquid characteristics that have to be taken into consideration.

Natural gas storage

Industry can also build on the knowledge obtained through the geological storage of natural gas, which has also been practised for decades. Few people, probably not even all the inhabitants, know that Berlin is placed on an aquifer that has been used for the storage of natural gas since the time of the Cold War.

Adjustment to scale takes time

History tells us that taking a new technology from the idea stage via the laboratory and to the market is a long and uncertain process. A successful intro-

Timeline:

How long have the different parts of the CCS chain and the CCS concept been in existence?

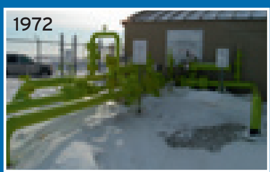
New technologies like CCS are seldom introduced overnight. There is often a significant period of learning and preparation before the technology is mature, the market accepts the product and a legal framework is put in place. Below you can travel through time on a journey that follows the development of selected parts in the CCS chain, beginning in the eighteenth century and ending in 2020.

In the eighteenth century: Carbon dioxide is one of the first gases to be described as a substance distinct from air. The Flemish chemist Jan Baptist van Helmont observes that when he burns charcoal in a closed vessel, the mass of the resulting ash is much less than that of the original charcoal.

1823: Carbon dioxide is first liquefied (at elevated pressures) by the British chemists Humphry Davy and Michael Faraday.

1920s: First application of the industrial separation of CO_2.

Early 1970s: The CO_2 capture technology is developed for commercial reasons e.g. food grade CO_2 for carbonating beverages. The idea of separating and capturing CO_2 from the flue gas of power plants gains much attention in the early 1970s as a possible inexpensive source of CO_2, especially for use in enhanced oil recovery (EOR) operations where CO_2 is injected into oil reservoirs to increase the mobility of the oil.



1972: First injection of CO_2 into an oil field in Texas, USA, for EOR purposes.

Late 1970s, early and mid 1980s: Several commercial plants that capture CO_2 from a power plant flue gas are constructed in the US. When the price of oil drops in the mid-1980s, the recovered CO_2 is too expensive for EOR operations, which forces the closure of these capture facilities. However, several more CO_2 capture plants are subsequently built to produce CO_2 for commercial applications and markets.

1986: The concept of CO_2 Capture and Storage (CCS) is presented for the first time by Norwegian researchers at the research institute SINTEF, who propose plans for gas-fired power plants with CCS.

1989: The Carbon Capture and Storage Technologies Program at Massachusetts Institute of Technology (MIT) is initiated. It conducts research into technologies to capture, utilize and store CO_2 from large stationary sources.

1991: Norway implements a carbon tax system as part of its response to climate change concerns. The Norwegian carbon tax provides the economic driver to motivate Statoil and partners to invest in a platform, separation and compression equipment and an injection well at the Sleipner gas field.

1992: The European Union starts funding CCS research projects.

1996: The world's first small-scale CO_2 storage project opens in the North Sea, The plant separates CO_2 from natural gas produced in the Sleipner field to increase the fuel value of the sales gas to meet customer and pipeline specifications. Normal practice would have been to vent the separated CO_2 to the atmosphere. Instead, the CO_2 is captured from natural gas recovered from the Sleipner field and injected into the Utsira deep saline aquifer, 800m below the seabed.

1996: Vattenfall begins performing a first analysis of the possibility to use CCS at potential coal-fired and natural gas-fired power stations in the future.

1997: Vattenfall devotes resources to monitoring the SACS project (Saline Aquifer CO_2 Storage) that Statoil is running at the Sleipner field in the North Sea.

1997: Working on the Kyoto Protocol, world leaders recognise the potential for CCS as a carbon-mitigation technology, but no incentives for CCS are included in the final agreement.

duction requires a great deal of persistency and patience, as well as good timing and competitive technology among the industrial players. We see this development all the time.

One lesson to learn is that the CCS technology can obviously not be introduced overnight, although it is clear that the individual links of the CCS chain are technically viable. The challenges of integrating and scaling up these technologies can only be met through the experience of building and operating commercial-scale CCS facilities in a variety of settings.

More expensive initially

As is often the case with new technologies under development, CCS will demand a lot of investment in the early phases. However, in the longer run, if the new technology can get through this process, mechanisms such as economies of scale and learning by doing, as well as incremental product development, will lower the costs of the technology.

Considering the nature of the projects, up-front payment is an important factor. The cost of a CCS demonstration plant is far too high for the industry to bear alone. The gap has to be closed and this must partly be done by public funding.

2001: Start of Vattenfall's CCS R&D project.

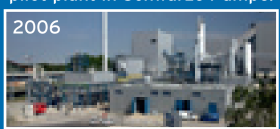
2002-2004: Vattenfall initiates sponsorship of oxyfuel test-rigs at five European universities.

2005: The Zero Emissions Platform, ZEP, is established by the European Commission to identify and remove the barriers to the wide-scale deployment of CCS in Europe. ZEP's goal is to make CCS commercially available and cost competitive by 2020. ZEP is a coalition of more than 300 experts from research, industry and NGOs working to implement CCS.

2006: The CO_2-capture industrial pilot unit of the Castor project, coordinated by the French R&D organisation IFP and financed by the European Commission, is launched at the Esbjerg power plant in Denmark operated by DONG Energy. It is the first installation to capture CO_2 from the flue gases of a coal-fired power station.

2006: Australia becomes the first country to establish a regulatory framework for CCS that allows the injection of CO_2 into the ground.

2006: Ground-breaking ceremony for Vattenfall's Oxyfuel pilot plant in Schwarze Pumpe.



2007: EU Heads of State and government call for up to 12 large-scale CCS demonstration projects to be operational by 2015.

2007: The UK Government launches the world's first competition for a large-scale CCS demonstration project on a coal-fired power station.

2007: The state of California in the US adopts an Emissions Performance Standard (EPS). As a result, new coal power plants must be equipped with CCS. The state of Montana in the US adopts a slightly different EPS, mandating at least 50% capture of CO_2 for new coal-fired power plants.

2007: The Weyburn project in Canada is launched as the most complete project at this time. The project includes CO_2 capture from a coal gasification plant, transport through a pipeline and injection and storage in an oil field, where it increases the oil production (EOR).

2008: Oxyfuel pilot plant in Schwarze Pumpe in operation.

2008: Vattenfall starts its CCS activities at Nordjyllandsværket with seismic investigations

2008: ZEP presents a detailed proposal for an EU Demonstration Programme in order to accelerate the deployment of CCS in Europe.

2008: The EU Climate Package is endorsed by the European Parliament. The biggest news when it comes to CCS is the revised directive for the EU's Emission Trading Scheme (ETS) where it is agreed to set aside 300 million emission allowances for funding CCS demonstration projects. This will equal about EUR 6-9 billion, depending on the future price of emission allowances.

2008: G8 leaders recognise the critical role of CCS in tackling climate change and recommend that 20 CCS demonstration projects be commissioned by 2010.

2008: The UK Energy Act 2008 is given Royal Assent. The Energy Act updates energy legislation to reflect the availability of new technologies, such as CCS. The act on CCS covers creating regulations that enable private-sector investment in CCS projects. In addition, the Energy Act ensures that legislation underpins long-term energy and climate change strategy. In December, EU leaders establish a legal framework for CO_2 storage and funding to support up to 12 CCS demonstration projects.

2008/2009: Announced by the Australian Government in September 2008, the Global CCS Institute is formally launched in April 2009 and becomes an independent legal entity in July 2009. It will work collaboratively with governments around the world, non-governmental bodies and the private sector to build confidence in CCS and help drive the international momentum needed to provide a solution to the urgent problem of climate change.

2009: Negotiations for a follow-up to the Kyoto Protocol culminate in December in Copenhagen, where it is hoped CCS will be recognised as a key tool for reducing emissions under international offset mechanisms, such as the Clean Development Mechanism (CDM).

2010: Vattenfall's Precombustion pilot plant in Buggenum in operation.

2010: Site preparation for Vattenfall's CCS demo in Jänschwalde.

2015: Vattenfall's CCS demonstration plant in Jänschwalde in operation.

2015: Magnum Precombustion demonstration plant at Eemshaven in operation.

2020: CCS technology commercially available.

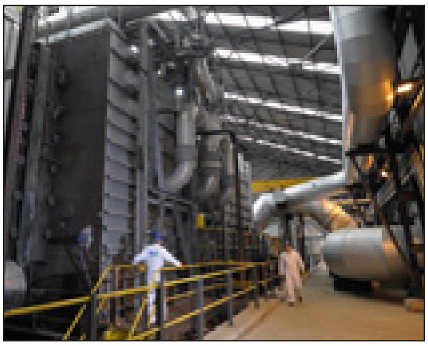
OxyCoal UK Phase 2 sucessfully completed

As we have previously reported, Vattenfall has participated in the OxyCoal 2 project led by Doosan Babcock, part of Doosan Power Systems. At its R&D Centre site in Renfrew, Scotland, the company has modified its existing test facility with the addition of 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 build and retrofit advanced supercritical oxyfuel plant.

Having completed close to 100 individual tests, the firing trials in the CCTF have demonstrated the successful operation of the 40 MW^t OxyCoal™ burner, both in air and in oxyfuel mode. Safe and stable operation has been achieved across a wide operational envelope. CO_2 concentrations of up to 85% (v/v dry) have been achieved at the economiser exit.

Operating experience

In the project, a lot of emphasis has been 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.



Three different methodologies for the safe and smooth transition between the air and oxyfuel firing modes have been developed and proven. Turndown from full load to 40% load has been demonstrated. The flame was stable and well rooted across the whole load range, although the length decreased as the load decreased, as in air firing.

Observations of flame and heat transfer

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.

The flame has been observed using both imaging equipment and viewing ports located along the furnace side wall. On our website, www.vattenfall.com/ccs, you can find short videos of the flame together with more text about flame observations and the heat transfer in the CCTF.

Behaviour of SOx and NOx

It might be expected that SO_2 concentration under oxyfuel firing would increase relative to the air-firing value in the same ratio as CO_2 concentration increases, i.e. five or greater. Air and oxyfuel-firing SO_2 values expressed as mg/MJ would then be coincident. However, analyses of the flue gas composition have shown that oxyfuel firing produces concentrations of SO_2 about three times higher than those produced when firing in air. Consequently, when SO_2 is expressed as mg/MJ the oxyfuel values are lower than the air-fired values, since SO_2 is removed from the process by adsorption in the fly ash and dissolution in the direct contact coolers.

Similarly, NO concentration under oxyfuel firing is approximately three times the value observed during air firing. Consequently, on a heat input basis (mg/MJ), the oxyfuel-firing economiser exit NO values are approximately one half of the values obtained during air firing. In both air and oxyfuel firing, there is a tendency for economiser exit NO concentrations to increase with increasing stoichiometric ratios. Effective NO formation under oxyfuel firing is reduced compared with air firing due to the elimination of thermal NOx formation and the fact that re-burn reactions reduce recycled NO.

Pleased with the cooperation

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 has been 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 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."

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

Vattenfall present at the 10th GHGT Conference

In September, the 10th International Conference on Greenhouse Gas Control Technologies opened in Amsterdam, the same city as the conference was first held in 1992. At that time, the CCS concept was new and fairly unknown. This year, more than 1 500 people gathered from all over the world to both share and hear about the latest news within CCS. The theme of the conference was "From research to reality", in many ways reflecting where Europe is right now on issues concerning CCS, not least for Vattenfall, which is developing demonstration projects in both Germany and the Netherlands.

A topic that attracted increasing attention this year compared to earlier conferences was public acceptance. In the panel of one of the discussions, called Public Perception and Acceptance – Lessons Learnt, Professor Niels Peter Christensen shared some of the experience Vattenfall has gained from CCS activities in Germany and Denmark. Prof. Christensen emphasised the importance of onshore storage and local storage locations (see also article on page 12) and presented the issues that should be given priority when developing suitable geological storage sites. For example, the safe storage of CO_2 was mentioned as a prerequisite and as an issue of great importance to the local population. Emphasis was given to the importance of, and opportunities for, creating local benefits in the area of the storage site. This can be done by forming alliances with local business, creating activities or jobs and so on.

Vattenfall's contributions

Vattenfall presented results and conclusions from its R&D projects and studies. A selection of these is described here. One of the papers was ***Flue Gas Cleaning for CO_2 Capture from Coal-fired Oxyfuel Combustion Power Generation*** (Yan, J. et al). The paper presented current progress in the area of flue gas cleaning for Oxyfuel combustion and significant improvements in understanding the characteristics of SOx, NOx, particulate matters (PMs) and non-condensable gas components in flue gas cleaning processes.

In Post-combustion and Pre-combustion for coal-fired power generation, CO_2 is selectively captured from the flue or fuel gases. In Oxyfuel combustion, on the other hand, CO_2 capture is a CO_2 enrichment approach, where the main purpose of flue gas cleaning is to control the non-CO_2 components for both the CO_2-capture process and the boiler operation. Based on conceptual development, fundamental understanding and practical tests at the Schwarze Pumpe Oxyfuel Pilot Plant, it has been proved that flue gas-cleaning systems have reached the performance level that can be considered achievable. The paper also concluded that there are generally no technical bottlenecks for most of the flue gas-cleaning technologies. Finally, it was suggested that further research should focus on comprehensive optimisation of the flue gas cleaning-processes combined with boiler and downstream CO_2 compressing processes. The knowledge obtained from the Oxyfuel Pilot Plant will be transferred and further proved in large-scale demonstration plant applications.

Dynamic simulations for transport and storage

The two papers ***Dynamic simulations of a carbon dioxide transport pipeline for analysis of normal operation and failure modes*** (Liljemark, S. et al) and ***Simulating rapidly fluctuating CO_2 flow into the Vedsted CO_2 pipeline, injection and reservoir*** (Klinkby, L. et al) described studies of load variations in energy production and captured CO_2 amounts and the effects on transport and storage systems.

The Postcombustion CCS project at Nordjyllandsværket has been developed as an early commercial CCS project. Nordjyllandsværket is a power plant designed such that the electricity output can be varied in accordance with market prices for electricity. These daily and hourly load variations need to be handled by the entire CCS system, from the capture plant to the reservoir. Therefore, in 2009, Vattenfall performed two studies in which the rapidly-fluctuating CO_2 flows into the Vedsted CO_2-pipeline. Injection well and reservoir were simulated along with the response of such transient variations in the pipeline, well and near the wellbore reservoir. One focal point was the occurrence of two-phase flow, i.e. the liquid CO_2 becomes gaseous due to pressure reductions. Phase changes will have implications for transport capacity and challenge the technical design of the entire system.

The results of the study that relates dynamic reactions in the pipeline with those in the storage reservoir indicate that high loads as well as shutdowns and shorter periods without flow can be handled by the modelled system. In the case of long periods of very low rates of CO_2 injection, problems arise with maintaining high CO_2 saturation in the near well reservoir and with phase changes in the pipeline and well. For low injection rates it will therefore be necessary to optimize phase conditions along the pipeline and at the well head. In the transport study the simulations demonstrate that preventive measures are required to help avoid and handle two-phase flow. For example, quick shutdowns and load changes led to the occurrence of two-phase flow. However, by controlling the flow through the final control valve, the two-phase flow was restricted to the vertical section of the pipeline (i.e. the injection pipe). Read more about the results from Vattenfall's R&D projects in an extended version of this article on our website: www.vattenfall.com/ccs

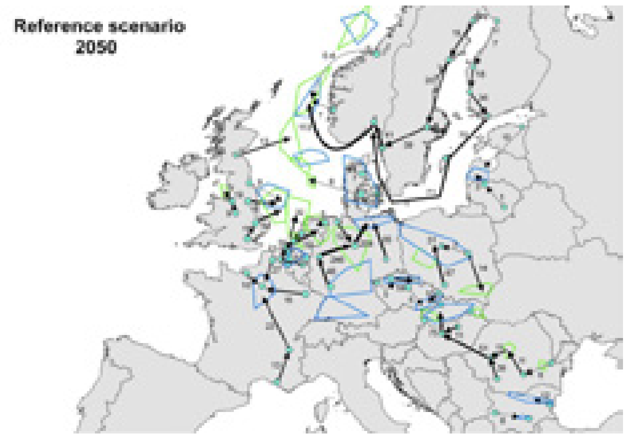
Storing CO_2 Locally

We are often asked the question: Should CO_2 be stored on land or offshore? Answering this question is not easy, but put simply – locally-produced CO_2 should preferably be stored as locally as possible.

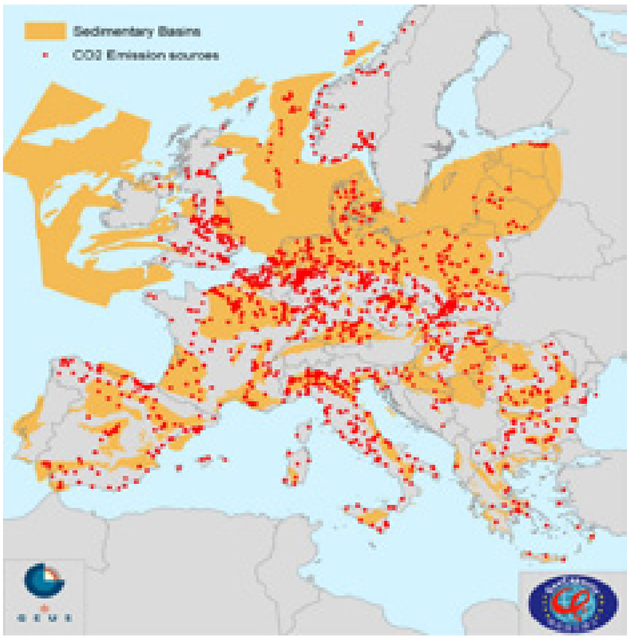
For CCS to become a major CO_2-abatement mechanism in Europe, sufficient capacity for the geological storage of CO_2 will be needed on land near the sources of the CO_2 as well as offshore when the deployment of CCS has become more mature. The great majority of European anthropogenic CO_2 is generated from a limited number of sites: power plants, oil refineries, steel plants, cement works, fertiliser plants and other major industrial installations. While the actual level and age of the activities at such plant sites vary considerably over time, the same locations are often used for many decades as it is quite difficult to create new sites for major infrastructure and industrial activities.

Geological basins suitable for CO_2 storage are unevenly distributed across Europe

Geological storage requires that some basic parameters are fulfilled: a depth below 700 – 800 metres and a porous storage reservoir with reasonable injectivity and with a tight cap rock above the storage reservoir. Nearly all sedimentary geological formations are deposited in marine basins or by water, such as rivers or lakes, when on land. Modern-day marine sedimentation occurs, for instance, in the North Sea or the Mediterranean, and along big rivers like the Ganges or the Mississippi. The geological basins suitable for the storage of CO_2 are unevenly distributed across Europe and the opportunity to store locally produced CO_2 in local geological storage sites is not always available, as it is, for instance, in the case of the U.K. This is clearly illustrated by the map below, produced by the EU GeoCapacity project (for more information see: www.geocapacity.eu).



An illustration from the CO_2Europipe publication of the so-called Reference scenario. This scenario is based on the current national CO_2 capture plans for 2020 from which the infrastructure has been further developed.



What is clear from the map is that the majority of Europe is located very far from the coast – often many hundreds of kilometres inland. This means that until a major pipeline infrastructure for the transport of CO_2 has evolved in Europe, local geological storage will be the key option not only for the first 10-12 CCS demonstration plants but also for the majority of the early commercial CCS plants expected from 2020 and onwards.

In a recently published study on future potential European CCS infrastructure one of the conclusions underscored the need for storage on land: 'Discarding onshore storage is likely to render CCS impossible for large parts of Europe', (CO_2 Europipe project, September 2010).

In conclusion, locally-produced CO_2 should preferably be stored as locally as possible. However, the majority of European countries are located far from the coast and potential CO_2 storage sites are unevenly distributed. For CCS to become a major CO_2-abatement mechanism in Europe, sufficient capacity for the geological storage of CO_2 will be needed on land near the sources of the CO_2 as well as offshore when the deployment of CCS has become more mature.

Enabling a voice for CCS in the Polish energy sector

Energy and heat generation in Poland is mainly based on the combustion of coal and lignite. A document published in 2008 by the Ministry of Economy, called "Polish Energy Policy until 2030", states that "National resources of hard and brown coal play an important role as energy security stabilisers". The document envisages one or two CCS demonstration plants by the year 2030, though there is no mention of deployment once the technology has been demonstrated. However, the energy companies in Poland seriously consider CCS as a chance to continue using coal for energy generation, while at the same time reducing their CO_2 emissions. That is why the largest energy companies operating in Poland, Vattenfall among them, have established the Polish Clean Coal Technologies Platform.

The ambition of the Polish Platform is to establish and support the necessary and sufficient conditions for the commercial use of low-carbon coal technologies in the Polish energy industry. The work performed in the Polish CCS Platform concerns exploring CCS issues, sharing the knowledge between the employees of the member companies and giving them an opportunity to learn about CCS. Some companies in Poland carry out their own work in this area.

Three working groups

There are three working groups in the platform: Technical, Public Acceptance and Legal. The Technical working group is concerned with the technical conditions for the development of the technology in Poland and with the conditions for financing the development and implementation of the technologies. The Public Acceptance working group is particularly interested in supporting public campaigns about CCS. The Legal working group monitors legislative processes regarding CCS in Poland and in the European Union and is interested in environmental conditions and the financial aspects of CCS. The group supports the Polish public administration in the implementation of legislation relating to CCS.

The Platform has established good co-operation with scientific, business and political stakeholders involved in CCS. The Platform co-operates, for instance, with Polish research institutes and geological institutes in the field of CO_2 storage sites in Poland. Co-operation with other companies interested in CCS technologies has also been established.

Study visits

The Platform is enabling the voice of the Polish energy sector to be heard: representatives of the Platform take part in seminars, conferences, consultations and actions supporting the development of CCS demo plants. This year, the Platform has organized study visits to the Bełchatów CCS demonstration site, Borzęcin and also to Vattenfall's Schwarze Pumpe Oxyfuel pilot plant. The aim of the visits was to learn about practical experience of the development of the CCS technology – both in regard to storage and to the capture of CO_2 from fossil-fuel burning installations. The idea of a study visit to Borzęcin, which belongs to the Polish Oil and Gas Company, originated from the willingness to learn about Polish experience of the geological storage of gases, including CO_2. Borzęcin is a place where acid gases have been geologically stored in the natural gas bearing structure for 15 years.

Andrzej Kiełbik from Gazoprojekt S.A.and Jacek Kurowski from Vattenfall Poland.

Valuable knowledge and experience sharing

The participants emphasized that the study visits enabled them to learn about the practical experience in relation to CO_2 capture and storage. "It is definitely worthwhile for our members to get to know the actual experience in the field of CCS and to base their judgments on real knowledge of that technology. It is particularly important in Poland, where electricity is generated primarily from fossil fuels," says Jacek Piekacz, Head of Vattenfall Poland and President of the Polish Clean Coal Technology Platform.

The issues discussed also included the activities of the Polish administration in relation to CCS as well as the legal issues. There is obviously a whole range of other issues worth discussing, such as financing CCS, commercialisation and the legal framework for the whole process. Almost 40 experts mainly from Polish energy companies and the public administration took part in the event. In the coming years they may be involved in the development of CCS in Poland.

European Coal Days

The event European Coal Days took place in the European Parliament between 8 and 12 November. The goal of the event was to present all the facets of the European coal industry – from its contribution to security of supply, the impact on nature, new technologies like CCS and so on. The event was organised by Dr. Christian Ehler, a Member of the European Parliament, and the European Association for Coal and Lignite (EURACOAL). Vattenfall was involved in organising the event together with RWE Power.

The event was opened by Günther Oettinger, Commissioner for Energy, who spoke about the challenges facing the coal and energy sectors. However, the best-attended event during the three days was the Round Table on Coal, dedicated to the role of coal within a future energy mix. The speakers included Philip Lowe, Director-General for Energy in the European Commission, and Dr. Hartmuth Zeiß, from Vattenfall Europe.

Issues discussed

In the discussions at the European Coal Days, it was mentioned that the concerns regarding security of supply and cost efficiency are strong arguments for a diverse mix of different energy resources. A large number of countries are and will be dependent on coal and electricity generation remains the primary application for this kind of fuel. To make the use of coal acceptable for the climate, CCS should be developed and made a commercial solution. Strong support for the demonstration phase of capture technologies and the issue of social acceptance for the geological storage of CO_2 were also discussed, as were the role of legal frameworks and public funds dedicated to the support of CCS development. CCS is dependent on a supporting legal framework. Additional focus centred on innovation and efficiency in power plants and the use of indigenous resources, as well as on how further research in the field of low-carbon coal technologies can contribute to the acceptance of coal in the future.

Vattenfall organised debate

Vattenfall also organised a debate entitled "Clean coal for Europe – making CCS work". During the Debate, Dr. Hartmuth Zeiß said: "CCS is one of the technologies with crucial importance for climate protection from a sustainability angle." He added that the development of CCS would sustain important industries, and the resulting value creation and employment situation. An investment-friendly legal framework and political support are major prerequisites for the successful rollout of CCS.

The hearing in the Committee on Industry, Research and Energy (ITRE) of the European Parliament was linked with the event, and Jacek Piekacz from Vattenfall Poland gave an introductory speech there in which he spoke about the future energy mix in the EU. He said that the challenge for a sustainable future is to combine economic development and energy security with measures to effectively reduce CO_2. The commercial availability of CCS depends on a reliable and supporting legal framework, quick implementation of the CCS Directive, realistic criteria for storage safety, liability provisions and other issues and, finally, substantial EU and national funding in the demonstration phase.

The European Coal Days were accompanied by an exhibition dedicated to security of energy supply, safety and quality for the environment, social acceptance and technologies for future implementation. The participants were mainly the Members of the European Parliament and their assistants, representatives of the European Commission, particularly from DG Energy and DG Research, and representatives of coal and energy companies and associations.

ON THE OTHER SIDE OF THE BRIDGE –

Increased use of biomass

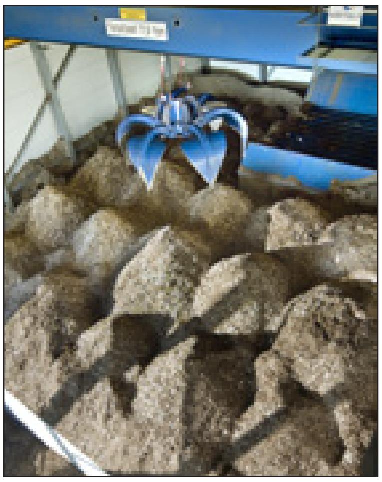
Vattenfall recently launched its new strategic objectives. These state that Vattenfall should reduce its CO_2 exposure and grow in low CO_2-emitting energy production by 2020. The ambition is to decrease absolute CO_2 emissions from 90 Million* tonnes to ~ 65 Million tonnes by focusing on wind power, nuclear power, biomass, hydropower and gas. Vattenfall is also committed to optimising the existing coal portfolio regarding CO_2-emissions and CCS is one method of achieving this. Another method is to invest in biomass co-firing in the existing hard coal-fired power plants. The report "Biomass for heat and power - opportunity and economics" states this by noting that biomass can reduce emissions of fossil carbon dioxide by between 55 and 98 per cent.

*2009

A significant part of the CO_2 reduction, 10 million tonnes by 2020, is to come from replacing hard coal in existing plants with biomass. This corresponds to 5 Million tonnes biomass (dry) and will require development of the fuel to allow direct replacement and high co-firing rates to minimise the modifications required in the power plants. Incentives will be important, at least initially, while in the longer term the cost reductions for biofuel and higher future costs for CO_2 will pave the way for a large penetration of biomass.

Examples of increased use of biomass within Vattenfall

The new straw-burning Unit 8 at the Fyn power plant in Odense, **Denmark**, officially commissioned on 21 April 2010, is one example of the increased use of biomass within Vattenfall. The unit is fuelled using 170 000 tonnes of straw annually (more than 300 000 large bales), replacing 100 000 tonnes of coal, which means that the atmosphere will be spared 245 000 tonnes of fossil CO_2 annually.



In **Finland**, two new biomass-fired units were commissioned in 2009 in Lammi and Vanaja, and one will be commissioned in Käenoja at the end of 2010, with a combined installed capacity of about 70 MW. The new turbine in the power plant at Myllykoski has increased the efficiency of the plant. In 2010, the share of renewable fuels in Vattenfall's production in Finland will reach 38 per cent, which is 10 years in advance of the EU's target for the share of renewable energy in Finland. In **Sweden**, a combined heat and power station was recently built in Jordbro for the combustion of biomass and waste wood. The plant increases fuel flexibility and thereby ensures stable prices for the district heating system, and was inaugurated in October 2010.

In **Poland**, Vattenfall is increasing the use of biomass at the Zeran and Siekierki combined heat and power plants, and the mix of biomass in combustion will more than double in 2010 compared with 2009, entailing the combustion of 140 000 tonnes of biomass. This means that CO_2 emissions amounting to 190 000 tonnes per year will be avoided. In **Germany**, Vattenfall is already today using more than 3 600 GWh of biomass fuels, of which the main part consists of biogenic fractions of waste. Ongoing projects include the construction of biomass-fired combined heat and power plants.

Supply security

Securing large quantities of biomass at competitive prices has been a problem. This is one of the reasons why Vattenfall has decided to create an international portfolio of supply contracts. To secure a stable supply of biomass fuels that meets strict sustainability requirements, Vattenfall is establishing an international biomass portfolio as a complement to locally-sourced fuels. One of the international suppliers is a company in Liberia that produces wood chips from old, non-productive rubber trees.

Biomass for heat and power - great potential for biomass as an energy source

The report "Biomass for heat and power - opportunity and economics" states that biomass can reduce emissions of fossil carbon dioxide by between 55 and 98 per cent, even if it has been transported over long distances. The aim of the report is to compile data and information on the advantages and disadvantages of biomass compared to other types of energy – principally fossil fuels.

Moreover, the report states that co-firing biomass in a coal-fired power plant is an efficient way of reducing fossil emissions. This makes biomass a key factor for achieving the EU's emission targets. However, for this to happen the use of biomass must increase to a level equivalent to all other renewable energy sources combined.

Thus, the report shows great potential for biomass as an energy source. But in order to exploit it, the quantities of available biomass must increase and an international trade in biomass must be established. To increase the rate of use of biomass, guideline action from politicians is needed. There is also a relationship between energy production and the traditional use of biomass. The profitability of energy production depends on other products extracted in the process. So, the expansion must take place in a way that does not expose the rest of the industry to risks. There is also a need for stricter environmental frameworks and legislation in order to ensure that this development does not jeopardise the sustainable use of natural resources.

The report was issued by a consortium of organisations that represents various environmental organisations, the forest products industry and the energy industry, Vattenfall among them. The WWF has also been involved in this work and endorses most of its key conclusions. Analyses were also contributed by the management consulting firm McKinsey & Company.

People working with CCS at Vattenfall

In the Netherlands, Vattenfall is preparing tor the large-scale implementation of the CCS technology by building a pilot plant, within the so called CO_2 Catch-up project. Radosław Gnutek, who works at Vattenfall in the Netherlands, is Project Engineering Manager of the construction part of the pilot plant and also Project Manager of the CO_2 Catch-up R&D.

The overall objective of the CO_2 Catch-up project is to demonstrate a pre-combustion CO_2 capture technology at the Buggenum IGCC plant in order to generate knowledge in the form of useful data and to become confident in the operation of the plant. The results produced in the pilot plant must be applicable for the development of state-of-the-art tools to be applied in the design process of the large-scale capture installation in the Magnum IGCC plant.

Tell us about your job?

"My main responsibility is to supervise the engineering process during the design and realisation phases of the pilot plant project. Additionally, as the Project Manager of the R&D part of the CO_2 Catch-up project, the main objective is to coordinate the work of two teams of colleagues, namely the researchers and the plant operation crew to ensure sufficient alignment between them," says Radosław Gnutek.

Radosław Gnutek describes what makes this job interesting: "The thrill of doing something new and pushing the energy industry forward is what I like the most in my job. The possibility of dealing with a wide variety of some of the brightest minds in the field of CCS research makes my work very challenging but also highly rewarding".

Preparation work for starting the unit in parallel with start of a testing period

After 18 months of construction and commissioning work, the team is currently preparing to start the unit. Radosław describes the time schedule in more detail: "First, the systems of the plant will be tested for proper functioning and then a number of performance tests will be executed to fulfil the contractual requirements of the plant supplier. In parallel with this we are preparing for a testing period of approximately two years. The researchers have been working on the project for more than a year now. Their activities are organized around four main topics: plant performance, water-gas shift, CO_2 absorption, and fouling and corrosion."

The current preparation involves the following tasks:

1. Building mathematical models, which will help explain phenomena observed during the plant operation.
2. Defining specific test objectives and the scope for test runs to be executed during the plant operation.
3. Performing additional tests in laboratories

"In addition to this we are in direct contact with other parties busy with similiar test facilities", says Radosław Gnutek.

Biggest challenges ahead

The research programme is very ambitious and executing all the planned test runs in the given time span will be difficult. It is also expected that the amount of information received after the start of operation will be very large. Radosław Gnutek describes the challenges in more detail: "The team tries to prepare for the swift and efficient processing of all of the results, but since we are dealing with research and development one can expect the unexpected to happen. Additionally, it is also very challenging to make sure that not only the measurements but also the experience and knowledge gathered during the research activities and the two-year testing period are preserved properly. They should be useful and accessible to other scientists and engineers than those who have generated the knowledge," says Radosław Gnutek.

However, the smooth operation of the plant, execution of all the planned tests, proper data analysis and preservation is only half of the success. "It will be a challenge to upscale the plant and to implement it in the Magnum Project, assuring the performance foreseen by the mathematical models and measured in the pilot plant," concludes Radosław Gnutek.

The CO_2 Catch-up R&D team works in partnerships and collaborations

The CO_2 Catch-up R&D team consists of a core group of 4 people. Approximately 13 researchers are involved in the research and there is a large operational team that operates and maintains the plant.

The R&D programme is performed in partnership with several Dutch research institutions such as Delft University of Technology, the Energy Research Centre of the Netherlands and KEMA, and in collaboration with the main technology suppliers.