Carbon Dioxide Capture, Transport and Storage (CCS)
Introduction

Cost-effective carbon dioxide capture, transport and storage are essential elements for reconciling the use of fossil fuels with environmental protection.

StatoilHydro and climate change
StatoilHydro acknowledges that emissions of greenhouse gases (GHG) are a major challenge, and we believe that a coordinated and powerful effort by governments, businesses and individuals is required to combat climate change.

StatoilHydro’s ambition is to remain an industry leader in terms of having a low climate impact from the activities that we are engaged in. We produce energy and remain committed to addressing climate issues. For us this represents both a challenge and an opportunity for technological innovation and value creation.

Within our industrial context we will:
• Apply our operational experience and technical competence to reduce GHG emissions from our activities
• Improve the energy efficiency of our installations and facilities
• Develop, test and implement new technologies to combat GHG emissions
• Develop a substantial and profitable new energy business

Research history in brief
Our earliest engagements in CO2 capture and storage were in the late 1980s when the Continental Shelf Institute was commissioned to carry out a pilot study on environment-friendly gas power and CO2 injection for improved oil recovery. Similar research began at the Statens Hydro Research Centre in 1989, but it was not until the early 1990s that internal activities really began to intensify.

At about the same time, StatoilHydro and partners decided that excessive amounts of CO2 contained in natural gas from the offshore Sleipner field should be stripped off and injected into a saline formation 1000 m below the seafloor. The first long-term CO2 storage to protect the natural environment started at Sleipner in 1996 where 1 million tonnes CO2 are injected each year.

Abbreviations
CASTOR: CO2 Capture and Storage Project
CCM: CO2 Capture Mongstad
CCP: CO2 Capture Project
CCS: CO2 Capture and Storage
CHP: Combined Heat and Power
CSEM: Controlled Source Electromagnetic Monitoring
EBI: Energy and Biodiversity Initiative
ENCAP: Enhanced Capture of Carbon Dioxide Project
EU: European Union
IEA: International Energy Agency
IKU: Sintef petroleum research
GHG: Green House Gases
GTL: Gas To Liquid
HMR: Hydrogen Membrane Reformer
HSE: Health, Safety and management
IGR: Improved Gas Recovery
IPR: Improved Oil Recovery
IV: Joint Venture
LNG: Liquidified Natural Gas
LPG: Liquidified Petroleum Gas
NERC: Natural Environment Research Council (UK)
PEL: Progressive Energy Limited
R&D: Research and Development
SACS: Saline Aquifer CO2 Storage Project
TCM: European Technology Centre Mongstad

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The authors are indebted to the following StatoilHydro staff for providing information and/or reviewing the manuscript: Trude Sundset, Ole Østrem and Chief Researchers.

Author: R&D project CO2 Value Chain
Contact person: Henrik Solgaard Andersen, hsand@statoilhydro.com
Cover: The Sleipner platforms Sleipner Riser and Sleipner A to the left connected to the Sleipner Treatment platform to the right. (Photo: Øyvind Hagen.)

Introduction
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Cover: The Sleipner platforms Sleipner Riser and Sleipner A to the left connected to the Sleipner Treatment platform to the right. (Photo: Øyvind Hagen.)
To learn as much as possible from the Sleipner case, Statoil and the IEA Greenhouse Gas R&D Programme set up the SACS project (phases 1 and 2, 1998-2000) with financial support from the EU. R&D work was shared among 7 major European geo-science research institutions and all results have been published. This has led to international dissemination of the Sleipner experience with global applications in mind. The SACS project was followed by the CO2 Store project (2003-2005), that addressed the long-term predictions of CO2 storage and the transfer of methods to onshore and near shore industrial sites. The experiences from these two large research programmes are documented in the report “Best practice for the storage of CO2 in saline aquifers”. (www.CO2store.org). Our large CO2 storage projects continue to be used in R&D studies and today storage data from the In Salah and Snøhvit fields are also used as basis for international research.

In 1998 StatoilHydro worked on the development of integrated oil-gas-CO2 value chain – called Hydrokraft. The concept comprised pre-combustion CO2 capture from a 3 x 400 MW gas power plant to be transported offshore and used for IOR at the Grane oil field. The project was stopped due to the economics at that time, but the learning was used to focus the CO2 capture R&D activities. Just into the new century the challenges connected to first long-distance offshore CO2 pipeline and sub-sea injection at the Snøhvit field lead to research on the thermodynamics of CO2 with relevant impurities. This knowledge has proven to be crucial for all aspects of the CO2 value chain.

After the merger in 2007 StatoilHydro formed a large R&D project on CCS called the CO2 value chain project. The objective is to develop competence, tools and technology within CCS for StatoilHydro’s current and future operations, including future challenges connected to extra heavy oil gas power, liquified natural gas (LNG) and gas to liquids (GTL) production. Most of StatoilHydro’s R&D is conducted in cooperation with partners. We are involved in several large joint industry projects (JIP) co-funded by the EU, as well as National research councils.

Awards
In 2002 StatoilHydro received two major awards: “The World Petroleum Congress’ technology development prize” for its pioneering efforts in underground carbon dioxide storage; and “The World Summit Business Award for Sustainable Development Partnerships”. These awards testify that StatoilHydro’s long-term efforts in environmental stewardship are paying off both in terms of industrial application and global awareness.

Green man award
In 2006 StatoilHydro Senior advisor Olav Kårstad received the “Green Man Award” from the IEA Greenhouse Gas R&D Programme for his long-standing national and international commitment to carbon dioxide research and innovative carbon management.

The technology options
All five elements in the technological tool-box for mitigating climate change are important. StatoilHydro have focus on four out of the five.

Mitigation of climate change can take many forms. Within the energy sector, however, we know about five tools in our technological tool-box. As shown in the figure they are: energy efficiency, fuel switching, renewables, CCS and nuclear power.

StatoilHydro is currently actively working in four of these areas. Our activities within renewable energy are increasing within our New Energy business unit. In our operations the efficient use of energy and CCS is on top of the agenda.

Mitigation of climate change can take many forms. Within the energy sector, however, we know about five tools in our technological tool-box. As shown in the figure they are: energy efficiency, fuel switching, renewables, CCS and nuclear power.

In Norway the Norwegian CO2-tax on offshore operations has made a significant impact on energy efficiency since 1991. StatoilHydro has pioneered not only CCS (e.g. Sleipner), but also electrification of offshore platforms from a hydro-powered land grid (e.g. Troll, Gjøa) and the use of highly efficient (combined cycle) power plants on offshore platforms (e.g. Oseberg). Conversion from coal to oil or natural gas for power production will reduce the CO2 emission significantly.

The technological tool-box for mitigating climate change in the energy sector: The tools are energy efficiency, fuel switching, renewables, CO2 capture and storage (CCS) and nuclear power. These principal technological tools can produce the zero-carbon energy carriers electricity and hydrogen. Illustration source: Freund, Kårstad “Keeping the Lights on”. Universitetsforlaget, 2007.
The Sleipner project, North sea

The Sleipner asset registered two world firsts in pursuit of environmental protection – large-scale offshore carbon dioxide separation and injection into a geological formation 1000 meters below the seafloor. By 2009, 11 million tonnes of carbon dioxide were stored instead of emitted.

The present industrial partners are ExxonMobil, StatoilHydro and Total.

The StatoilHydro-operated Sleipner field\(^1\) is a large oil & gas producer in the Norwegian sector of the North Sea. It was discovered in 1974 close to the British/Norwegian sector divide. The daily gas export expected for 2009 is 24 million cubic metres and 4 000 Sm\(^3\)\(^4\) of light oil.

During field development planning in 1990, it was realized that the 9% CO\(_2\) content in the natural gas would have to be reduced to meet the sales gas specification of maximum 2.5%. The technical experts came up with the unprecedented idea of capturing the CO\(_2\) offshore and injecting it into a saline formation beneath the Sleipner installations. In this way, the Sleipner asset would minimize CO\(_2\) emissions – the prime motive – while avoiding environmental taxes\(^5\).

Despite its pioneering nature, this became the partner-approved solution.

An amine based absorption process was selected for CO\(_2\) capture, because it was deemed more compact than competing systems. One of the greatest challenges, however, was to scale down the process plant sufficiently so that it could be accommodated on an offshore platform. Even so, the ‘miniaturized’ version of the CO\(_2\) capture module weighed 8 200 tonnes.

By the time the field came on stream in October 1996, the Sleipner organization registered two world firsts: the installation of a large-scale offshore CO\(_2\) extraction plant at the Sleipner Treatment platform; and the facilities for injection from the Sleipner A platform.

**CO\(_2\) capture from natural gas at high pressure**

The first stage in the Sleipner CO\(_2\) capture process entails the mixing of an amine-water solution (i.e. alkanolamines) with the natural gas in two parallel columns (absorbers A and B), both of which are kept at 100 bar pressure and moderate temperature (60 - 70 °C). The amine – an organic compound derived from ammonia – selectively absorbs the CO\(_2\) by weak chemical bonding. Thereafter it is transferred to a 15 bar flash drum in which the co-absorbed hydrocarbons are removed. The amine is subsequently heated and de-pressurized to 1.2 bar (absolute) pressure in a second flash drum where the CO\(_2\) is boiled off. By now the CO\(_2\) is almost pure, >95% CO\(_2\).

As the semi-lean liquid amine still contains residual CO\(_2\), some 10% is subject to thermal regeneration where the CO\(_2\) is stripped off by steam in a desorber column operating at a temperature of 120 °C. The remaining semi-lean amine is then mixed with the regenerated amine and pumped back to the absorbers for a new separation cycle.

**CO\(_2\) compression and injection**

Once the CO\(_2\) has been captured, its pressure is boosted by four compressor trains to 80 bara prior to being transferred to the Sleipner East A platform for pumping into the base of the Utsira formation. Since 1996 about 1 million tonnes of compressed CO\(_2\) have been injected annually. The injected CO\(_2\) is now in a dense phase and has physical properties like a liquid.

The well casing and other hardware used in the capture and injection plant is made of stainless steel, because liquid water mixed with CO\(_2\) produces corrosive carbonic acid (H\(_2\)CO\(_3\)).

The investment costs for compression and injection amounted to some USD 80 million in 1996 (CO\(_2\) capture costs excluded). Although this was a considerable sum, the partners would otherwise have faced a considerable tax bill if the CO\(_2\) had been vented into the air.

**Deep geological formation and cap rock characterization**

The formation into which the CO\(_2\) is being injected is named the Utsira Formation. This formation covers an area of 26 000 square kilometres that...
mainly lies within the Norwegian sector of the North Sea. It was deposited in a north-south oriented strait 2 - 12 million years ago. The formation in the Sleipner area has a thickness above 200 m and is an exceptionally porous and permeable sand formation lying 700 - 1000 m below the seafloor. A large storage capacity and excellent reservoir properties alone are not sufficient to make the Utsira Formation an attractive target for CO2 storage. Safe storage also requires that a suitable caprock overlies the reservoir. The caprock of the Utsira Formation consists of 200 – 300 m of mudstones, which are overlain by mostly fine-grained glacial deposits. These mudstones have permeabilities of about 1 microDarcy with pore throat diameters less than 40 nm. This corresponds to capillary entry pressures above 2 MPa. Such small pore throats thus create a capillary seal for a 400 m column of CO2.

Time-lapse seismic data

Injection of CO2 into the Utsira Formation. Seismic monitoring results showing the seismic from 1994 – 2001 and 2008 and the evolving plume as seen in amplitude maps. 10,1 million tonnes of CO2 have been injected in period 1996-2008.

Seismic monitoring
When injection of CO2 started in 1996 it was uncertain whether the dynamic behaviour of the injected CO2 could be monitored using modern geophysical techniques. StatoilHydro decided to perform time-lapse seismic surveying because the sound velocity difference between salt water-bearing (higher velocity) and CO2-bearing (lower velocity) sandstones is significant. Time-lapse seismic, also known as 4D seismic, involves comparing the results of 3D seismic surveys repeated with time intervals.

So far seven seismic surveys have been conducted: a baseline survey in 1994 prior to CO2 injection and monitoring surveys carried out in 1999, 2001, 2002, 2004, 2006 and 2008, during CO2 injection. The seismic surveys have not only successfully traced the injection of the CO2 and expansion of the CO2 plume, but have also yielded extremely sharp images of the Utsira formation’s internal structure.

A particularly striking result is that the distribution and migration paths of the CO2 are strongly controlled by intra-formation mud rock horizons. With an extraordinary seismic layer detection limit of about 1 metre or less, much of the CO2 can be seen to have migrated upwards between the Utsira Formation mud rock terminations, as witnessed by a distinct seismic chimney-like column appearing on repeated seismic surveys.

Only 1/6 of the injected CO2 has so far reached the uppermost sand layer, the rest being trapped under thin shales within the Utsira formation. The CO2 plume is elongated, and the flow is controlled by the topography of the sealing shales. The diverse vertical distribution of CO2 means that much of the rock volume will be exposed to CO2, making storage mechanisms as residual trapping, dissolution in the formation water and interaction with the rock minerals more effective. This large part of the CO2 plume is not at all exposed to the cap rock yet.

Gravimetric monitoring
StatoilHydro’s latest offshore time-lapse micro-gravity surveying technique has been performed at Sleipner. This technique has been successfully used at the Troll field to image and monitor changes in the hydrocarbon gas-water contact. The technique depends on lowering a gravity instrument package onto permanent concrete blocks installed on the seafloor. The seafloor gravimeter contains three gravity sensors and three pressure sensors, which enable the instrument to monitor extremely small changes in gravity. Repeated high precision measurements potentially can provide more accurate calculations of the density of CO2.

A seven by three kilometer baseline survey was performed at Sleipner in 2002 and repeated in 2005. The accuracy has exceeded the expectations.

Between 2002 and 2005, three effects have caused changes in gravity: i) the CO2 injection, ii) hydrocarbon gas production and associated
water influx in the underlying reservoirs, and iii) height changes of the seafloor benchmarks caused by seafloor erosion and biological activity (fish). The three effects can be separated by multi-variable analysis, using measured height-changes and the knowledge of both CO2 distribution and gas reservoir geometry mainly based on seismic observations. The density is calculated with 95% confidence between 640 kg/m³ and 770 kg/m³.

**Flow modelling**

Whereas geophysical monitoring surveys can image the present distribution of injected CO2, reservoir simulations can predict how the CO2 will flow, distribute and be trapped in the future. Such models are updated on a regular basis as new data become available.

The models can also predict whether the CO2 could reach exploration or production wellbores from the Sleipner field, which could be potential leakage paths. Such understanding is especially important because the CO2 will not cease to move in the subsurface when the injection stops. Comparisons between prediction modelling and observations from monitoring are used to ensure that the rocks and fluid flow processes in the Utsira Formation are properly understood.

Buoyancy will drive injected CO2 from deeper to shallower positions within the Utsira Formation and move towards the cap rock. In this flow process the free CO2 is subject to three different trapping mechanisms, such as:

- Capillary trapping,
- Dissolution into formation water and
- Precipitation as minerals.

Capillary trapping is a mechanism by which fluid entering the pores of a formation is trapped and can not be removed. This mechanism appears instantly.

CO2 will dissolve in formation water. This water saturated with CO2 will be heavier than virgin formation water, and thus will start to sink. The buoyant CO2 and the sinking CO2-saturated water will drive convection within the formation. In the long term, all of the injected CO2 will have dissolved in the formation water of the Utsira Formation and the buoyant CO2 plume has disappeared. Modelling suggests that complete dissolution of the CO2 plume may take some thousand years.

Mineral precipitation is the final storage mechanism. The CO2 STORE project tested Sleipner reservoir sand and fluids as well as cap rock geochemically in laboratory and modelling. It shows that it will take geological time to have a significant volume precipitated.

### The Snøhvit project, Barents sea

StatoilHydro and partners have successfully started a second offshore carbon dioxide storage project at Snøhvit in 2008.

**Introduction**

StatoilHydro and partners¹ have started a second offshore CO2 storage for the Snøhvit field development outside Northern Norway. The production area extends across the Snøhvit field itself and the Albatross and Askeladden satellites. All three contain natural gas with 5 to 8 % CO2.

Snøhvit came on stream in 2007.

Snøhvit is the first LNG-based gas field development in Europe and also the first oil and gas development in the areas offshore Northern Norway. It is developed using subsea production installations in water depths of 250 to 345 metres and linked by a 143-kilometre multiphase flow pipeline to the processing and gas liquefaction (LNG) plant at the island Melkøya. The production capacity is 5.7 billion cubic metres of natural gas per year at full capacity.

¹ Petoro, Total, Gaz de France Suez, Amerada Hess and RWE-DEA.
The In Salah project, Algeria

CO₂ Capture and Storage at the In Salah Gas Joint Venture project has been going on since 2004 and has attained worldwide interest as an onshore CCS Demonstration case.

The CO₂ injection is part of the jointly operated Sonatrach-BP-StatoilHydro In Salah Gas Joint Venture (JV) operation in Algeria. The JV covers the development of eight gas discoveries in the central Saharan region of the country, and delivers 9 billion cubic metres of natural gas per annum.

The gas fields contain CO₂ with concentration ranging from 1 to 9%, whereas export gas specifications require a CO₂ concentration less than 0.3%. To achieve this target and avoid emissions, the capture and storage of 1.2 million tonnes of CO₂ annually is necessary. The CO₂ is stripped off from the gas stream using an amine process and injected into 3 wells in a saline formation surrounding one of the gas fields – Krechba at 1800 m depth.

Three horizontal CO₂ injectors were drilled between 2003 and 2004. The wells were drilled into the reservoir formation below the gas-oil contact outside the northern and eastern periphery. The reservoir thicknesses vary from 15 to 24 m within a broad anticlinal fold. According to the field development plan, the injected CO₂ should slowly migrate upwards and reach the production reservoir after it has been depleted.

In addition to the valuable experience the JV partners have gained on the operational aspects of CO₂ storage they have also set up a R&D activity named the In Salah Joint Industry Project (In Salah CO₂ storage JIP). Being onshore opens opportunities to test alternative monitoring technologies and improve the understanding of CO₂ behaviour in the subsurface. Novel well data has been acquired to further investigate and verify the nature of the cap rock seal, surface and down-hole gases have been measured and a range of geophysical monitoring methods is being tested.

One of the most interesting developments has been the use of satellite radar data to monitor...
surface changes related to the subsurface injection and production. Novel analysis of time-lapse satellite data, allow subtle ground uplift and subsidence to be detected, and found to be a few mm per year. This surface deformation can be related to the pattern of injectors and producer wells and provides a new vital cost-effective monitoring technique.

Experience gained from the performance of the 3 horizontal injection wells and the monitoring data have revealed the importance of understanding the rock mechanical behaviour of CO₂ storage sites. The Krechba reservoir contains natural fractures and joints which influence the development of the CO₂ plume and the injection capacity of each well. Monitoring so far shows the CO₂ plume to be elongated parallel to the present-day stress field. Work is underway with our research partners to better understand these processes using geo-mechanical, geochemical and flow models to predict the long-term fate of CO₂ more accurately. Thus the In Salah project will complement the pioneering projects at Sleipner and Snohvit and stimulate the worldwide adoption of CO₂ storage.

Further Investigations in CO₂ storage

The injections at Sleipner, In Salah and Snohvit has already given extensive knowledge on the behaviour of CO₂ in the subsurface, and improved methods to monitor this. However, StatoilHydro will continue significant R&D efforts on CO₂ storage. The research effort addresses storage capacity assessments, and better understanding, modelling and monitoring of CO₂ flow within the underground.

Mapping of storage sites

The available volume for CO₂ storage at a certain location depends on the injection strategy and the trapping mechanisms that can be mobilized. Thus research on new injection strategies to maximize the extent of capillary trapping and dissolution of CO₂ into the formation water is interesting; as such trapping provides a vast potential possibility for storage of CO₂ outside structural closures. Also interactions between the formation water, the rock and CO₂ must be understood to be able to model and optimize long-term storage. CO₂ may dissolve some minerals, and combine with other minerals to result in permanent (mineral) trapping.

Monitoring and flow models

Modelling of the movement of CO₂ in the reservoir, and to make the models match the excellent seismic data from Utsira is challenging. The uniqueness that the Utsira data represent makes them an ideal laboratory for further investigations of simulation models and methodology for CO₂ flow in reservoirs.

The first testing of Controlled Source Electromagnetic Monitoring (CSEM) was performed in September 2008 above the Sleipner injection site. Potentially this method can provide data complementary to the seismic and gravity, and thus make it possible to improve the geophysical interpretation and optimize storage monitoring.

In the coming years data from new monitoring methods and other types of storage reservoirs like In Salah and Snohvit will be used internally as well as externally to improve our understanding of CO₂ storage processes and our capability to model them.

Environmental impact

Several R&D activities are started to look at environmental impact in the marine environment caused by a possible leakage of CO₂. Both the development of monitoring technologies to identify leakages and identifying environmental impact of increased CO₂ content is investigated.
CO₂ transport

To be able to optimize the total CO₂ chain, StatoilHydro is investigating the fundamental behavior of CO₂ mixed with relevant impurities.

The CO₂ storage projects are dependant on a CO₂ stream pure enough to be efficiently transported and injected into the storage formation. A liquefied CO₂ stream can be very efficiently transported in large amounts by pipeline over long distances. Such transport of liquid CO₂ has been ongoing more than 30 years on shore. The Snøhvit CO₂ pipeline going 153km offshore to a subsea injection well demanded new knowledge for design and operation. New modelling tools and procedures had to be developed for safe operation. To verify these models a CO₂ pipeline test facility was established at the StatoilHydro laboratories in Trondheim, Norway.

The aim of the test facility is to experimentally verify depressurization. The facility consists of a down-scaled pipeline of 139 m length between a low and a high pressure tank. CO₂ is brought back from low to high pressure with a pump or compressor.

A test matrix of experiments has been set up and executed for parameter evaluation and validation of a CO₂ two-phase transient flow model. This matrix included steady state experiments of liquid, gas and two-phase flow at various mass flows, temperatures and pressures. Next transient depressurisation experiments from various initial pressures were performed. The deviations between model and experiment were considered low enough to conclude that the model is experimentally verified. The effect of adding impurities to the CO₂ is planned for future experiments. Additional tests to measure heat flux into a real piece of the Snøhvit CO₂ pipeline submerged in different soils has been linked to the test facility. By combining the heat transfer results with the depressurization results the CO₂ pipeline model can achieve better accuracy.

CO₂ Capture

CO₂ can only be efficiently captured from large point sources. High concentrations of CO₂ sources are attractive due to low capture cost. To really make a difference CO₂ capture from power plants is necessary.

According to the IEA, 56% of the worlds anthropogenic CO₂ emissions can be allocated to 7500 point sources emitting more than 100 000 tons of CO₂ per year. As shown in the figure, power plants are the dominating source. Thus, to address the major volumes of CO₂ emissions it is necessary to capture CO₂ from the flue gas of coal- and gas-fired power plants and other energy processes (steam boilers) The low total flue gas pressure and relative low molar fractions of CO₂ in flue gas (typically ranging from 3.5% in natural gas-fired to 12% in coal-fired power stations) are challenges to capturing the CO₂ in a cost- and energy efficient way. While the majority of GHG emissions come from coal-fired power stations, StatoilHydro has so far been focusing on capture from natural gas fired power production. Our current target for CO₂ capture from gas-fired power stations is:

- To achieve an electrical energy efficiency better than 50%.
- To have a CO₂ capture efficiency above 85%.
- To reduce the CO₂ capture cost and
- The technology must not have harmful local emissions or discharges.

Currently three capture technologies are proposed:

- Post-combustion: Fossil fuel is combusted with pure oxygen. This process produces an exhaust containing mainly CO₂ and water, and water can be condensed by cooling.
- Pre-combustion: This implies to remove the carbon from the fuel before combustion. Currently the fossil fuel is first converted to synthesis gas, which is a mixture of hydrogen and carbon monoxide. In a second step the carbon monoxide reacts with steam to form CO₂ and more hydrogen. The CO₂ can then be separated from hydrogen at relatively high pressure using conventional technologies similar to those used for natural gas.
- Oxyfuel: Fossil fuel is combusted with pure oxygen. This process produces an exhaust containing mainly CO₂ and water, and can be condensed by cooling.

All three technologies share the major challenge that the separation process is energy intensive. However, as soon as the CO₂ is captured it can be compressed and efficiently transported and injected. In the short term post-combustion technology has the advantage that it can be applied to conventional energy and power plants. In the longer term the inclusion of other fuel types and technological development within material technology and fuel cells will make it necessary to keep a wide approach and follow up R&D within all the three capture technologies.

<table>
<thead>
<tr>
<th>Sector</th>
<th>CO₂ emissions %</th>
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<tbody>
<tr>
<td>Cement production</td>
<td>~7%</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>~5%</td>
</tr>
<tr>
<td>Oil refineries</td>
<td>~6%</td>
</tr>
<tr>
<td>Petrochemical industry</td>
<td>~3%</td>
</tr>
<tr>
<td>Other</td>
<td>~3%</td>
</tr>
<tr>
<td>Coal power generation</td>
<td>~60%</td>
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<tr>
<td>Gas power generation</td>
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<td>Fuel oil power generation</td>
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<td>Cement production</td>
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<tr>
<td>Petrochemical industry</td>
<td>~3%</td>
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Showing CO₂ emissions from 7500 large point sources. More than 75% of the emissions are related to power production. Source IEA.
### Post-Combustion

Removing CO₂ from the flue gas with amine absorption is the most mature technology. It has recently received competition from the chilled ammonia absorption.

Post-combustion is the most mature technology for capturing CO₂ from power and energy plants, but still, it has not been built and operated on a large scale. The absorption of CO₂ with an amine solvent is known from natural gas purification and ammonia industry. Several suppliers are available with different solutions at variable maturity level. StatoilHydro has performed a long series of studies to use this technology for CO₂ capture from planned gas-fired power plants at Kårstø, Tjeldbergoden and Mongstad. Illustration page 20 shows the amine process in its most general form.

Post-combustion technology also has been dominating our R&D efforts up until now. The most important projects are CASTOR and its follow-up CESAR (www.co2cesar.eu). Both are partly EU funded with nearly 30 partners from R&D, academia, suppliers and operators. The largest amine based post-combustion pilot unit in the world was built in 2005 at the DONG-operated coal fired power plant in Esbjerg. It has a capture capacity of 1 tonne CO₂ per hour. The CO₂ recovery rate is feasible and has been proven in pilot tests. Moreover, two new amine solvents have been tested with promising results. The next step in CESAR is to test even more solvents, and also to measure the emissions to air.

In 2005, StatoilHydro started to support laboratory scale development on a new type of post-combustion technology called “Chilled Ammonia”. It is based on an absorption/desorption cycle using ammonia instead of amine. The energy efficiency and the HSE-performance seemed promising and a fast track development program was chosen for this technology. In February 2008 the first pilot unit was started by Alstom in Wisconsin. These two technologies are the candidates for demonstration at the European Test Center Mongstad.

The amine process in its most general form.

### Pre-Combustion

Pre-combustion is to convert fossil fuels to a gas stream containing mainly hydrogen and CO₂. The CO₂ is then removed and the hydrogen used as a fuel for heavy duty GE Frame 9 turbines. It was demonstrated that combustion of a mixture of hydrogen and nitrogen was technically feasible and that NOx levels could be kept below acceptable limits.

Several improvements to pre-combustion technologies are under development. In StatoilHydro research on a ceramic hydrogen membrane reformer has been ongoing for 8 years. This technology combines the three major steps of pre-combustion technology: Reforming, shift and CO₂ removal into one integrated step, aiming for a significant improvement in energy efficiency.
European CO₂ Technology Centre Mongstad

The European CO₂ Technology Centre Mongstad is unique due to its ambitions, its flexibility of CO₂ sources and technologies and its cooperation of international companies from both oil and power industry.

StatoilHydro is a partner in the “European CO₂ Technology Centre Mongstad” (TCM). TCM is based on an agreement between the Norwegian government and StatoilHydro and the objective in the first phase is to test two post-combustion CO₂ capture technologies, i.e. amine and chilled ammonia technology. TCM is the first step in the implementation of CO₂ capture at the Mongstad refinery. The test facilities are planned to capture 100,000 tonnes of CO₂ annually. Other ambitions of the TCM project are:

- Development of technologies for CO₂ capture capable of wide national and international deployment
- Reducing cost and technical and financial risks related to large scale CO₂ capture
- Testing, verification and demonstration of CO₂ capture technology owned and marketed by vendors

The chilled ammonia technology is still under development and therefore represents higher technological uncertainty. The aim at TCM is to verify it for large-scale use. A very important part of the test program is to verify the HSE performance of the different capture technologies, in particular the local emissions to air and discharges to water.

CMM – CO₂ Capture Mongstad

In connection with establishing the Mongstad energy project, StatoilHydro and the Norwegian government entered into an implementation agreement. Under this agreement StatoilHydro undertook to prepare an overall plan for future CO₂ capture at Mongstad, “Master plan”.

The Master plan addresses the most important challenges and sums up key issues associated with the technical feasibility of carbon capture at Mongstad. This is the first step along the way towards full-scale carbon capture at Mongstad. The project is still in an early stage and much work remains to be done.

The Master plan report⁵ describes the facility, technology and the most important risks associated with realising full-scale carbon capture. The plan addresses the principal challenges and summarises the need for studies and verification of individual technical solutions. Carbon capture on the scale of millions of tonnes per year from exhaust and flue gases is unique on a global basis. The master plan confirms that carbon capture is possible and describes two main alternatives as to how this can be done at Mongstad.

Oxyfuel

Using pure oxygen instead of air in combustion generates a flue gas consisting of mainly CO₂ and water, thus simplifying separation of CO₂.

Oxyfuel technology for CO₂ capture from coal-fired power production is now being tested at the Schwarze Pumpe test facility in Cottbus, Germany (built and operated by Vattenfall). StatoilHydro is supporting these tests through participation in the ENCAP project. Oxyfuel is also an important task in the CO₂ Capture Project (CCP) where the performance and costs of Oxyfuel heaters and boilers are being studied. StatoilHydro has been part of the CCP project team since 2000. A more advanced oxyfuel boiler concept based on chemical looping combustion is also being developed with support from CCP.

Oxyfuel shows the principle of the Oxyfuel technology. There are a tenfold of different Oxyfuel cycles more or less advanced. Typical potential application areas are boilers and heaters and gas turbine cycles.
Carbon dioxide value chains

StatoilHydro has included CO₂ management in the planning of all new projects. Throughout our business we encounter a range of challenges related to CO₂. We have CO₂ emissions from many different sources and need to develop technology to reduce emissions or capture CO₂ from these. Future areas where CCS is relevant are in the production of Extra Heavy Oil, Gas to Liquids, Liquefied Natural Gas, Oil Refining as well as Natural Gas Processing. These different applications will need different technical solutions.

StatoilHydro is involved in research and development in the total CO₂ value chain: Different geographical locations call for different alternatives for CO₂ storage and transport. Different geological formations have different challenges, so both the injection strategy and the monitoring programme need to be fitted to the specific setting.

Tomorrow’s world

StatoilHydro is working towards a vision of carbon dioxide-free energy from fossil fuels and excellence in environmental stewardship.

Back in 1993, StatoilHydro outlined a scenario for an emissions-free future with natural gas as energy source as shown in the figure. Even if renewable and maybe nuclear energy production should be added in this drawing, the most plausible 21st century scenario is that fossil fuels remain a large energy source, while electricity and hydrogen can be the energy carriers. Our ambition is to provide clean, energy-efficient solutions for our customers.

As StatoilHydro sees natural gas as the energy source also for hydrogen production, our ongoing commitment to CO₂ management takes on a new dimension.

To promote energy related innovation, StatoilHydro has established the ‘New Energy’ business unit which seeks industrial applications arising from the latest energy research. The mandate is to develop opportunities in sustainable energy production and renewable energy – including those arising from CO₂ management.