Annual Report 2014

BIGCCS

International CCS Research Centre

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Why we need research on CCS

Global warming is largely caused by carbon dioxide (CO_2) emissions from the use of fossil fuels. To avoid unacceptable climate change, the global average temperature rise must be limited to two degrees relative to pre-industrial times. On the other hand it is predicted that the world's energy consumption will grow by 56 per cent between 2010 and 2040. The world will continue to use fossil fuels for many years to come, after all 85 per cent of the primary energy use in the world is fossil energy.*

Fortunately, there are several things we can do to reduce the emissions, these are after all caused by human activity. A much worse case would be global warming caused by completely uncontrollable factors.

Carbon capture, transport and storage (CCS) is a technology that prevents large amounts of carbon dioxide from fossil fuels entering the atmosphere.

According to the International Energy Agency (IEA), CO_2 capture, transport and storage is the third most important measure to limit global warming by two degrees.

The technology involves capturing CO_2 produced from fossil fuels, compressing it for transportation and then injecting it deep into underground formations at carefully selected and safe sites, where it is permanently stored and isolated from entering the atmosphere.

CCS is already happening today. But we still need more research and innovation to make CCS realise its potential. This is what BIGCCS is contributing to every day.

Chairman of the Board
Dr. Nils Røkke

* Source: Climate Change 2014: Mitigation of Climate Change, IPCC WGIII US Energy Information Administration International Energy Outlook 2013 (IEO2013)

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FME
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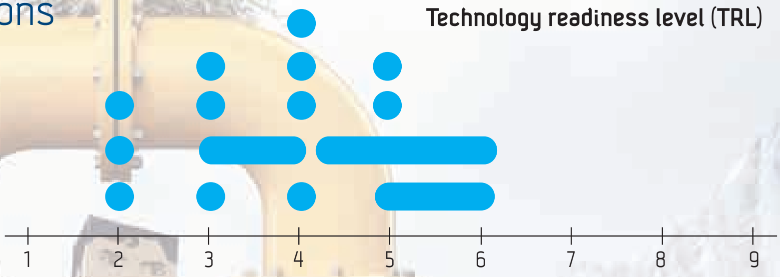
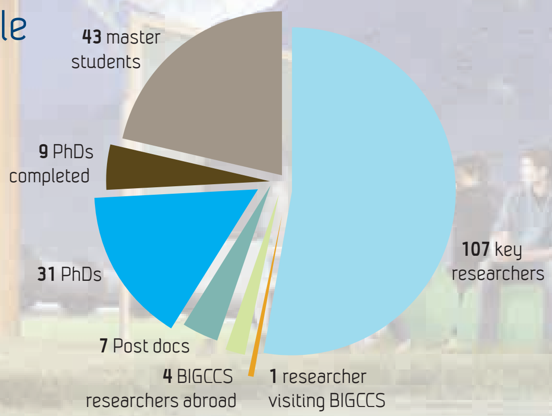
2014 in numbers

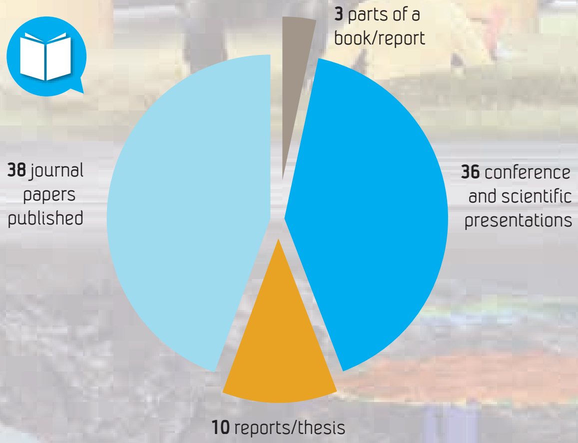
Innovations



People



Publications



Contents

Message from the Centre Director

Another year in the duty of CCS has passed and it is time to look back. With the urgent need for CCS action, it is a great responsibility to lead one of the largest CCS R&D efforts world-wide. In BIGCCS we have a continuous focus on improvement - both in how we carry out the research, what we focus on, but also on how we reach out with our results and innovative ideas for smart and efficient CCS. We are proud of our new web. You are all invited to visit **www.bigccs.no**.

Also this year we are proud to count our achievements and as this report shows they are many and includes 19 innovations, 139 deliverables, 90 publications, seven newsletters, three new KPN projects, several Climit Demo projects, nine oral presentations and nine posters at GHGT-12, and last, but not least the Greenman Award which was given to Professor Hallvard Svendsen at GHGT-12.

In BIGCCS we are privileged to have a fantastic Scientific Committee lead by Professor May-Britt Hägg from NTNU. This year I would like to pay a special tribute to the Scientific Committee and thank them for the encouraging and valuable feedback on the scientific work and collaboration opportunities around the world.

I would also like to express my gratitude to the BIGCCS Board for the fruitful discussions and very interesting visit to GDF SUEZ' offices in Paris last spring, where the Board also was offered the possibility to visit the natural gas storage facility in Germigny-sous-Coulombs.

In BIGCCS we build trust between researchers representing many of the CCS research fields. This is the strength of our Centre, and is shown in many of our results. Some examples are CO_2 well integrity, a completely new method for analyses of membrane systems, and CO_2 pipeline integrity were a new method for analysing fracture propagation and arrest is developed.

Enjoy the reading!

Dr. Mona Mølnvik

Vision and goals

The BIGCCS Centre enables sustainable power generation from fossil fuels based on cost-effective CO_2 capture, safe transport, and underground storage of CO_2. This is achieved by building expertise and closing critical knowledge gaps in the CO_2 chain, and by developing novel technologies in an extensive collaborative research effort.

The overall objective is to pave the ground for fossil fuel based power generation that employ CO_2 capture, transport and storage with the potential of fulfilling the following targets:

- 90 % CO_2 capture rate
- 50 % cost reduction
- Fuel-to-electricity penalty less than six percentage points compared to state-of-the-art fossil fuel power generation

Find out more: **www.bigccs.no**

Research plan and strategies

The research topics covered by the BIGCCS Centre require in-depth studies of fundamental aspects related to CO_2 capture, CO_2 transport, and CO_2 storage.

Research relies on a dual methodology for which both laboratory experiments and mathematical modelling are employed. The modelling and experimental activities share the same theory or hypotheses, and seek answers to the same questions from different points of view.

The emphasis is on building expertise through quality research at a high international level, both within the research tasks, the post-doctoral work, and through the education of PhDs.

There is a two-way coupling between the modelling and experimental work: Experiments are necessary for developing and verifying models. At the same time, developing and understanding models will lead to an improved understanding of the described phenomena.

In BIGCCS, research takes place within international networks of scientists, including the participation of world-class experts. The emphasis is on building expertise through quality research at a high international level, both within the research tasks, the post-doctoral work, and through the education of PhDs.

New knowledge is in part gained through novel CO_2 capture technologies integrated with industrial processes, supporting the development of research strategies for the Centre.

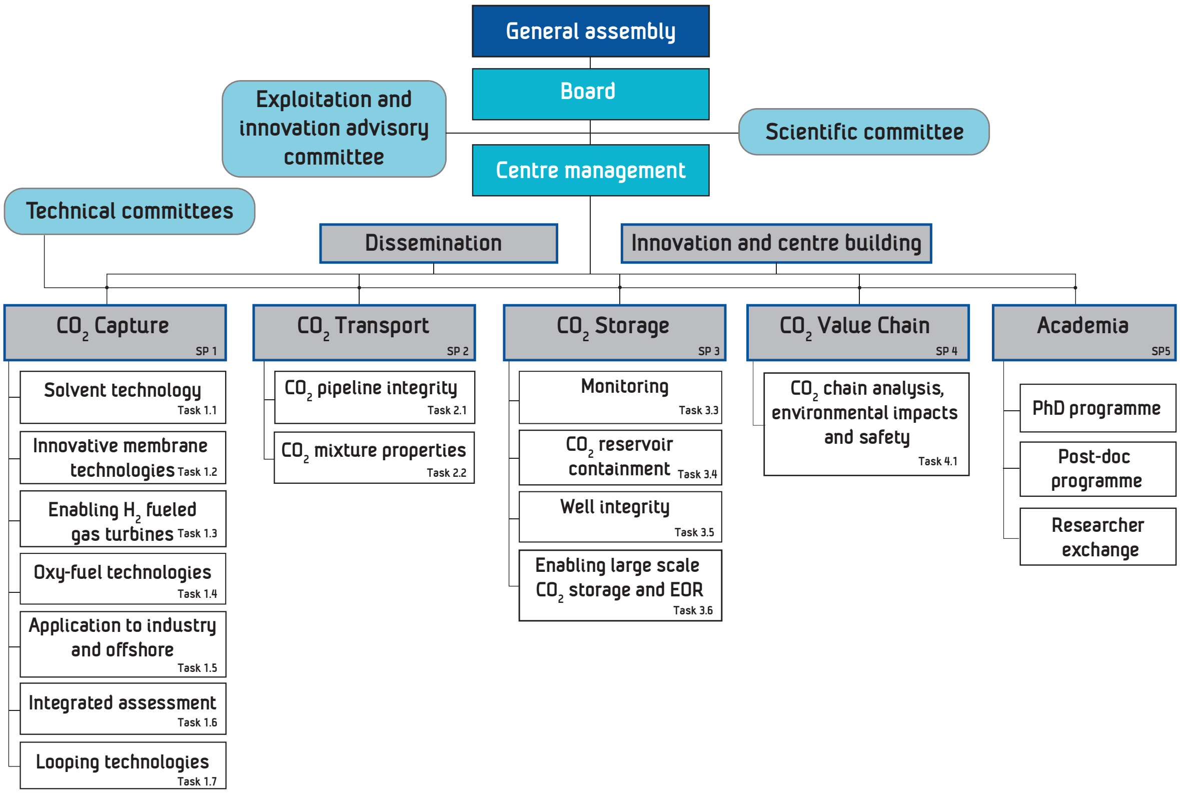
In CO_2 transport, the combination of theories and models describing pipeline fracture resistance and CO_2 fluid dynamics requires a coupled analysis of the problem. Different numerical simulation methods are used and will create improved understanding of the two-way influence between the CO_2 fluid and the pipeline.

In CO_2 storage, the basic knowledge of CO_2 behaviour in the reservoir and rock mechanics when influenced by CO_2 is used in aggregated reservoir and basin models.

Organization

Organizational structure

The Centre is organized with a General Assembly, a Board, a Scientific Committee, an Exploitation and Innovation Advisory Committee and a Centre Director. The BIGCCS governance structure is shown in the figure below.



The General Assembly (GA) is the ultimate decision-making body, ensuring that operations are carried out in accordance with the Consortium Agreement. The GA had its 2014 meeting in Trondheim on September 24. Ole Kristian Sollie (Shell) is the Chairman of the GA.

The Board is the operative decision-making body of the Centre. Two meetings were held in 2014; on May 20 (Paris, France) and on November 27 (Trondheim). Members of the Board in 2014 were: Dr. Rune Bredesen (SINTEF), Mr. Peter Britze (GEUS), Dr. Per Ivar Karstad (Statoil), Mr. Ole Lindefjeld (Conoco-Phillips), Mr. Ole Kristian Sollie (Shell), Mr. Tom Steinskog (GDF SUEZ), Mr. Thorbjørn G. Svendsen (Gassco), Prof. Hallvard Svendsen (NTNU), and Dr. Rune Teigland (TOTAL). Chairman of the Board is Dr. Nils Røkke (SINTEF).

The Scientific Committee (SC) is an advisory committee with leading international academics giving guidance to the Centre related to scientific progress. The SC is chaired by Professor May-Britt Hägg (NTNU).

The other members are: Dr. Sally M. Benson (Stanford University), Dr. Susan D. Hovorka (University of Texas at Austin), Dr. Alan Kerstein (Sandia National Laboratory), Dr. Gary T. Rochelle (University of Texas at Austin), Dr. Matthias Wessling (AVT-RWTH, Aachen), and Dr. Forman A. Williams (University of California at San Diego). The SC had its 2014 meeting on November 5, in connection with the GHGT-12 conference in Austin, Texas, USA.

Centre Director is Dr. Mona J. Mølnvik, who is leading the Centre Management Group, consisting of all Sub-Programme leaders, and the Centre administration.

Work breakdown structure

BIGCCS consists of five Sub-Programmes; CO_2 Capture, CO_2 Transport, CO_2 Storage, CO_2 Value Chains, and Academia. Each Sub-Programme is broken down into different Tasks, which are shown in the figure on the previous page.

As a response to recommendations from industry partners and the midway evaluation (carried out in 2013) the Sub-Programme on Storage was reorganized in 2014. The purpose of the reorganization was to increase the focus on enhanced oil recovery (EOR) as an opportunity for making a business case in CO_2 storage. New tasks were added to accommodate the EOR focus while other tasks were continued outside the Centre. The new tasks in SP Storage are: CO_2 monitoring technologies (Task 3.3), Reservoir containment (Task 3.4), Well integrity (Task 3.5) and Enabling large-scale CO_2 storage and EOR (Task 3.6).

Minor organizational changes were also done in the Capture Sub-Programme, where the alterations primarily were done to account for the integration of new KPN projects added to the SP during the last years.

Partners

The following organizations have been partners in the BIGCCS Centre during 2014:

Industry parties:

- ConocoPhillips Scandinavia
- Gassco
- GDF SUEZ
- Shell Technology Norway
- Statoil
- TOTAL E&P

Research institutes:

- British Geological Survey
- CICERO
- Deutsche Zentrum für Luft und Raumfahrt
- Geological Survey of Denmark and Greenland
- NTNU Social Research
- SINTEF Energy Research (Host Institution)
- SINTEF Petroleum Research
- SINTEF - SINTEF Materials and Chemistry

Universities:

- Norwegian University of Science and Technology
- TU München
- University of Oslo

Associated partners:

- Ruhr Universität Bochum
- Sandia National Laboratories
- University of Berkeley
- North Carolina State University
- RWTH Aachen University
- Georgia Tech
- Brigham Young University
- National Renewable Energy Laboratory
- Stanford University

Cooperation between partners

The actual research cooperation between the research and industry partners takes place at the task level. Task leaders coordinate activities and organize meetings between the relevant partners (technical meetings). During 2014, each task organized two technical meetings.

Once a year all SP and Task Leaders meet for a *Task Leader Seminar*. This year's seminar was held in Trondheim on May 9, and dealt with innovation and potentials for technology development in light of the of the latest IPCC report.

Two Sub-Programme Days were held in 2014 – the *Storage Day* on September 22 and the *Capture Day* on November 4. These meetings are in principle open to partners only, but also external resources have been invited. The topic for the Storage Day was results from on-going activities and priorities for future research on CO_2 storage to enable large-scale CCS. The Capture Day dealt with results and plans for the next years, and also had an open session with invited speakers.

The Centre organizes an annual *Consortium Day.* At this event all partners and researchers are invited, and the intention is to provide a snapshot of last years' activities and results. The BIGCCS Consortium Day 2014 was held at Scandic Lerkendal, Trondheim on September 23, with more than 50 attendees.

The *Centre Management Group* (CMG) consists of the SP leaders, the Leader for the centre building and dissemination activities, the Centre Director and the Centre Manager. Representatives from SINTEF Energy Research, SINTEF Petroleum Research, SINTEF Materials and Chemistry and NTNU are present. The CMG held 23 meetings during 2014, including one full-day *CMG seminar*, which focussed on future research priorities and possibilities for continuing BIGCCS. The focus of the CMG is to ensure that the annual work programme is carried out according to plan, and to oversee the day-to-day operations.

BIGCCS Board meeting in Paris, May 20, 2014. From left: Mona Mølnvik (SINTEF, Centre Director), Rune Teigland (TOTAL), Ole Lindefjeld (ConocoPhillips), Svein Solvang (Gassco) Nils Røkke (SINTEF, Chairman of the Board) Tom Steinskog (GDE SUEZ), Ole Kristian Sollie (Shell), Rune Bredesen (SINTEF) Åse Slagtern (Research Council of Norway), Britta Paasch (Statoil), Hallvard Svendsen (NTNU), and Kristin Jordal (SINTEF). (Photo: SINTEF)

Dr. Per Ivar Karstad
Head of New Value Chains in R&D
Statoil ASA

"The energy industry needs to develop low carbon solutions as a response to the climate challenge. Statoil will be part of the solution to this challenge. Fossil energy resources will be the dominant energy source in the future energy mix for many decades to come. CCS is the only technical solution to significantly reduce CO_2 emissions from these energy sources. CCS and BIGCCS is important for Statoil in being part of the solution to the climate challenge."

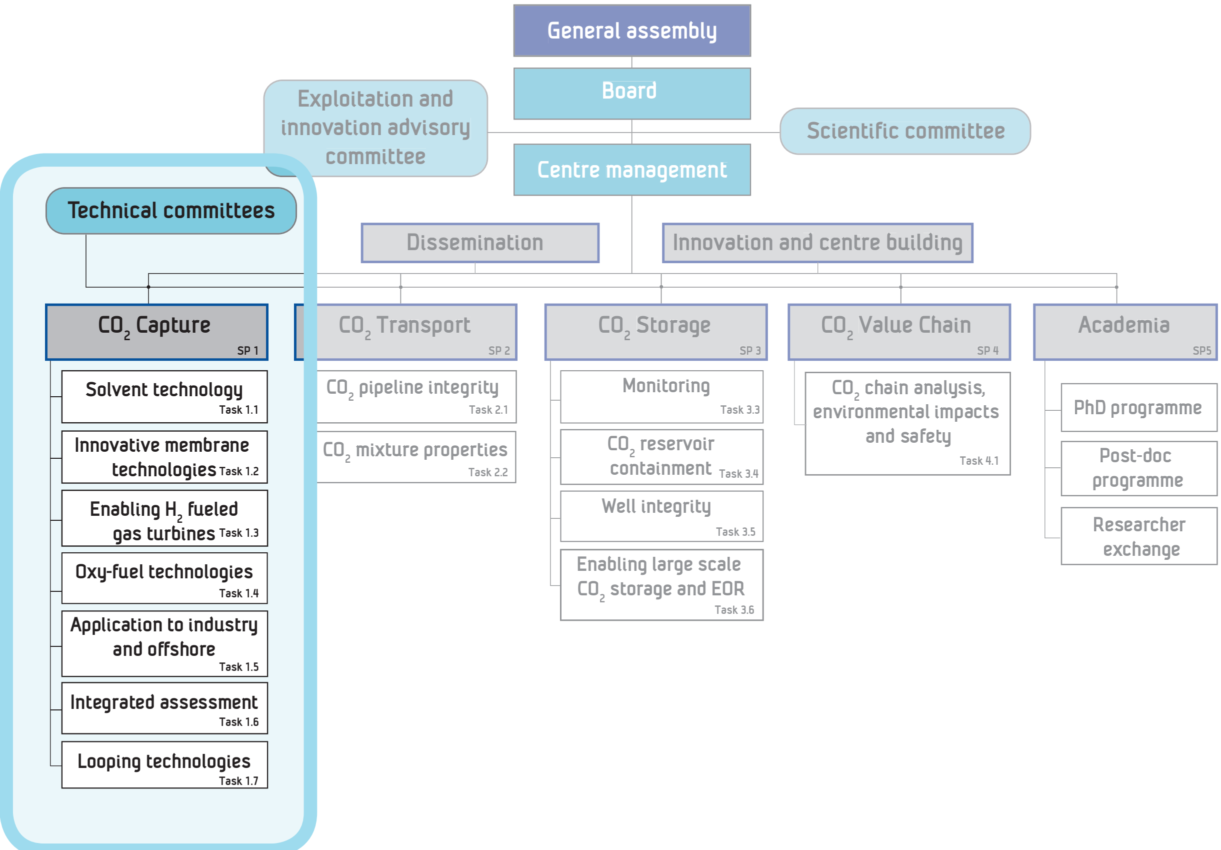
"The primary motivation is my concern about the dangers of global warming which are gradually unfolding in terms of increased coastal destruction and extreme weather events."

Dr. Andy Chadwick
Individual Merit Research Scientist
British Geological Survey,
Natural Environmental Research Council, UK

Partow Pakdel Henriksen

CO_2 capture (SP1)

Capture of CO_2 takes place before or after combustion, and combustion processes can be made cleaner. The overall aim is to reduce CO_2 emissions from being released into the atmosphere. Since the world still depends on fossil fuels for energy production, there is a need for technology to capture CO_2 from coal- and gas-fired power plants and from industrial sources.



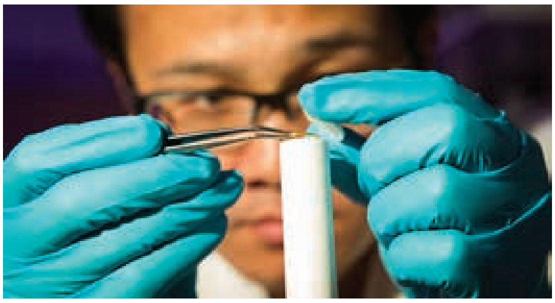
Summary of achievements

The CO_2 Capture Sub-Programme has achieved the followings:

- New class of precipitating absorbents with good absorption rates, easily dissolved precipitate and fast CO_2 desorption rate have been identified. A more simplified process for precipitating system for CO_2 capture has been proposed based on the properties of the new precipitating system. This process have possibilities to utilize waste heat in plants for solvent regeneration. Further this process offers possibility for higher pressure CO_2 recovery.
- Dynamic test campaign was completed in the Gløshaugen pilot plant. Dynamic model that can be implemented in various solvent based capture pilots has been developed. The dynamic model was implemented to represent the test result from Gløshaugen pilot plants and also a dynamic model for Tiller pilot plant was implemented.
- The long-term flux performance of symmetric hydrogen pre-combustion membranes has been tested up to 1500 hours in H_2 and CO_2 containing atmospheres at 1000C, and the degradation phenomena have been elucidated by post-characterization of the membrane material.
- A new, analytic mean flame shape model, that considerably improves present state-of-the-art approaches for prediction of flashback in ducts, is developed and validated versus Direct Numerical Simulation datasets.
- The technology based on flameless combustion (FLOX®) has been experimentally demonstrated in high pressure conditions at DLR and shown to be a good candidate to achieve Exhaust Gas Recirculation in the flue gas to be treated in post-combustion capture, while avoiding combustion stability issues.
- A swirl stabilized burner for semi-closed oxy-fuel gas turbine application has been tested under pressure for the first time in the HIPROX facility. This burner will be used in the demonstration oxy-fuel plant to be built through ECCSEL infrastructure funding from RCN.
- The 150 kW CLC rig has been installed at Tiller, and first non-reacting operation has been performed.
- Continuous operation of the 3 kW CLC attrition test rig in Oslo for more than 100 hours has been achieved, and four new batches of oxygen carriers for CLC has been produced and tested.
- A new dolomite based material for carbonate looping processes has been found to yield higher cyclic capacity and less deactivation than regular dolomite.
- Investigation of the IGCC process with Distributed Fuel Injection (DFI), proves that there is a potential for efficiency improvement in addition to resolving the challenges with H_2 combustion.
- Evaluation of an amine-based Novel Generic Solvent (NGS) to establish an additional benchmark for post-combustion CO_2 capture from Natural Gas Combined Cycles (NGCC) and to illustrate how adding improvements for amine capture (new solvent, reduced temperture difference in reboiler, Exhaust Gas Recirculation) can yeald a significant reduction in capture penalty.
- Improvement of a heat- and mass balance model for Chemical Looping Combustion, subsequently applied for an evaluation of steam generation in refineries.

Oxy-fuel burner in operation. (Photo: SINTEF)

- Development of a process concept for stand-alone H_2 production from coal with CO_2 capture, combining Pd-alloy membranes and low-temperature capture of CO_2. The conceptual process has a H_2 recovery of ~75% while producing the power required for low-temperature capture of CO_2 as well as H_2 liquefaction.



Wen Xing sealing ceramic hydrogen transport membrane for flux testing at high temperature. *(Photo: SINTEF/Werner Juvik)*

Yngve Larring at 3 kW CLC attrition test rig in Oslo. *(Photo: SINTEF/Werner Juvik)*

Highlights

(This text was first presented on the #SINTEFenergy-blog):
http://blog.sintefenergy.com/en

Øyvind Langørgen

Chemical Looping Combustion test rig at Tiller

In order to limit climate changes we need to cut CO_2 emissions. The burning of fossil fuels for electricity and heat production is still the largest source of global CO_2 emissions. Capturing the CO_2 emissions from these processes will be important in order to reach the needed CO_2 reduction. Chemical Looping Combustion (CLC) is a rather new and novel CO_2 capture technology closely combining materials, reactor and combustion science. In BIGCCS we are doing research and development on this in order to bring CLC forward.

CLC belongs to the oxy-combustion route for CO_2 capture. Fuel is burnt only with oxygen and not with air which is the normal when burning a fuel (e.g. as in your car engine, wood stove, gas burner etc.). The main benefit is that it produces an exhaust gas which consists mainly of CO_2 and water vapour since no nitrogen is involved as would be the case with normal combustion in air. This makes the CO_2 separation easy by just condensing out the water vapour.

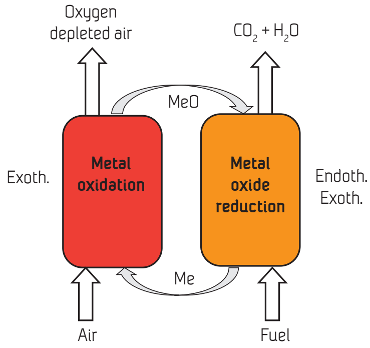
Chemical Looping Combustion (CLC) is a rather new and novel CO_2 capture technology closely combining materials, reactor and combustion science.

The clue in CLC is the way the oxygen is produced. The standard method for oxygen production is by cryogenic distillation of air at very low temperatures. CLC uses instead that metal particles can be rapidly oxidized in air at high temperatures, in the order of 850 – 1000°C. That is, the particles extract oxygen from the air. The resulting metal oxide particles are then transported to the fuel where the oxygen is released and used for burning the fuel. Thereafter they are transported back in order to continue the "looping" process as illustrated in the figure. This can be less energy intensive and costly than standard oxygen production methods.

The main challenges in CLC are development of suitable metal oxide particles as well as appropriate reactor and control systems for long time continuously operation. The metal particles must survive and do the job at high temperatures, they should ideally extract and release as much oxygen as possible in as short time as possible (some seconds) and they should not break down into fine powder, or agglomerate and clog into larger particles. The reactor and control system must ensure stable operation, high circulation of particles and full burn-out of fuel.

The most recent achievement is the installation of a large test rig of 150 kW capacity installed at Tiller during 2014. The rig is intended for gaseous fuels. The reactors are 6 meters high with diameter of 240 and 160 mm. At this size small scale effects are of minor importance and the results obtained can more easily be transferred to even larger test rigs and demos. Preliminary tests have been done, both at low and high temperatures, but at time being without fuel gas supply. The first tests with fuel gas supply and real reactive CLC operation is planned within 2014. The 150 kW rig is so far the last and largest step in the chain of development and infrastructure built up within the CLC activity of BIGCCS.

Installation of the 150 kW CLC rig. *(Photo: Øyvind Langørgen)*



Principle of Chemical Looping Combustion.

The most recent achievement is the installation of a large test rig of 150 kW capacity installed at Tiller during 2014.

Innovation and industry benefits

*** Technology readiness level**

Innovation	TRL*	Benefit / Impact
Precipitating system for post combustion CO_2 capture.	3	This technology will be of benefit to organizations that work towards reducing carbon footprint in the industries.
A power cycle scheme utilizing a novel hydrogen fuel injection concept through a porous diffuser.	2	Potential for efficiency improvement in addition to resolving the risk with H_2 combustion in an IGCC process with Distributed Fuel Injection (DFI).
Hydrogen fired gas turbine with exhaust gas recirculation (EGR	2	Today's concepts with hydrogen or syngas fired gas turbine (IGCC or pre-combustion) require to strongly dilute the fuel with nitrogen to achieve acceptable NO_x levels. This process costs 2 - 3 efficient points penalty. By applying high EGR rate, we show that combustion inherently generates low NO_x without the need for dilution, nor complex burner development.
Oxy-combustion with high temperature ceramic oxygen separation membranes has been described. The concept is to fully integrate the air separation unit (ASU) and the oxy-combustion chamber into a dense ceramic membrane combustor.	2	The concept has the potential of significant improvement in the heat integration of the membrane based Air Separation Unit and improved catalytic flame-less combustion.
Production of powder in small scale of 1-10 kg with equipment that is possible to scale up.	5-6	The innovation is important for Norwegian industry, institutes and university since they have the possibility to test production of new materials for different applications, reducing their cost and risk compared to larger scale test facilities.
The 3 kW test rig is designed to test attrition properties of oxygen carrier particles in dual circulating hot CLC rig.	4	This unique test rig will give valuable information on material strength on realistic operating conditions.

Academic achievements

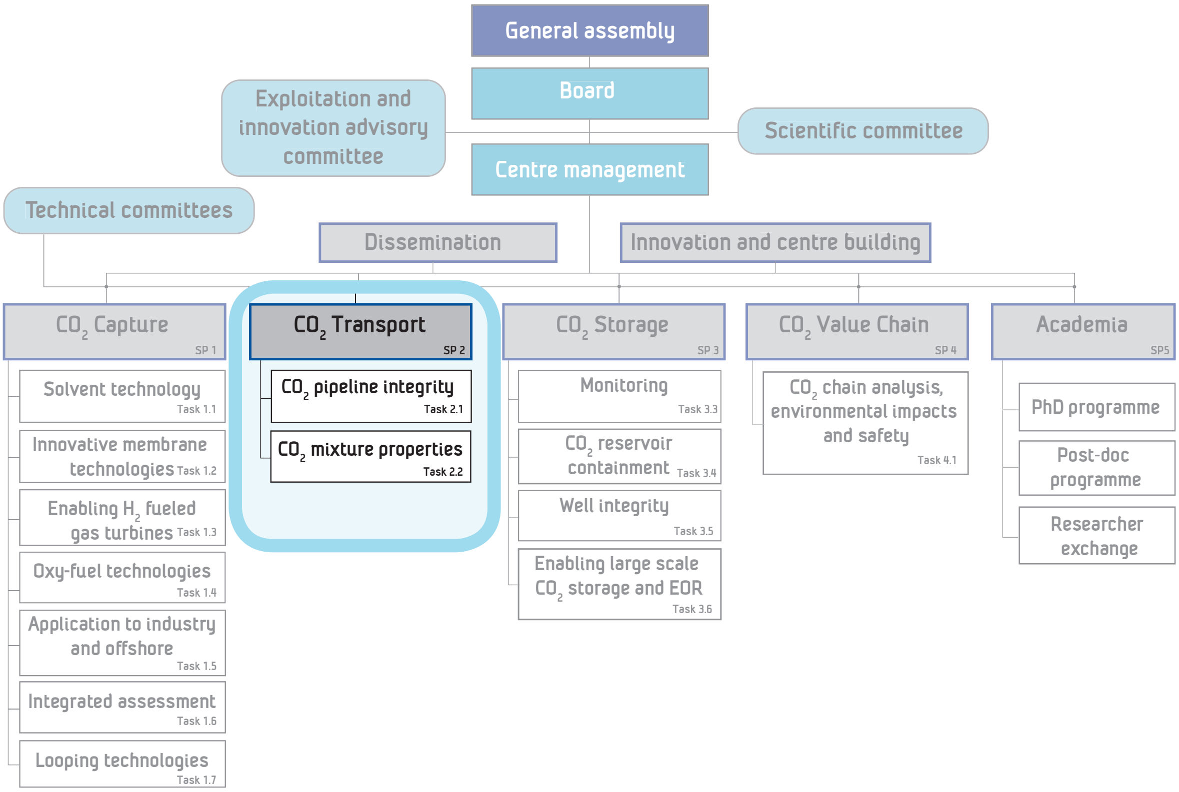
- PhD candidates; Xiaoguang Ma and Rafael A. Sanchez have successfully defended his PhD at NTNU. Rengarajan Soundararajana has submitted his PhD thesis. Einar Vøllestad and Camilla Vigen have successfully defended their PhD at UiO.


NORGAS ALAMEDA

Svend Tollak Munkejord

CO_2 Transport (SP2)

CCS deployment requires large quantities of CO_2 to be transported from the capture points to the storage sites. The objective of SP2 is to enable safer and more cost-effective design and operation of CO_2 transport systems. Two chief challenges are safe pipelines and accurate quantification of CO_2-mixture properties.



Summary of achievements

The work in the CO_2 Transport Sub-Programme is particularly relevant for safety, and therefore also economy. The CO_2 property data being acquired are necessary to perform accurate calculations. The first application will be transport, but accurate models for thermophysical properties will become more important also within other parts of CCS, as the concepts become more developed and greater accuracy is required. Specific achievements from SP2 include:

- BIGCCS has developed a coupled fluid-structure model which can calculate running-ductile fracture in transport pipelines, and which therefore can contribute to safe and economical CO_2-transport. The available experimental data for model development and verification are very scarce, but we are currently working on data from medium-scale experiments conducted in the DNV GL-led CO_2PIPETRANS project. We have been granted access to the data before they are published.
- BIGCCS has developed an equilibrium cell for gas-liquid equilibrium of CO_2-rich mixtures at pressures and temperatures relevant for CCS. The cell is now operational and producing high-quality data in ranges where few or no data were previously available. The data are required to develop new models and improve existing models for thermophysical properties. Such models are required to accurately design and safely operate CCS systems.
- Initial experimental data have been obtained for the speed of sound in the gas phase of CO_2-rich mixtures. Such data are also required in the development of accurate property models.
- The BIGCCS industrial partners have expressed interest both for the experimental data and the numerical models of SP2.
- In 2014, the competence-building project "Ensuring well integrity during CO_2 injection" was added to BIGCCS Task 3.5 Well integrity. The project combines knowledge developed within SP2 and SP3. In particular, the thermo- and fluid dynamical models developed in Task 2.1 are employed as a starting point.
- The work in BIGCCS SP2 was one important factor leading to the establishment of the IMPACTS EU FP7 project concerning the impact of impurities on CO_2 transport and storage. Indeed, the experimental facilities on thermophysical properties will also be employed in the IMPACTS project in 2015.
- The work in SP2 has also contributed to links being established with other leading groups internationally. A new project has been established on phase equilibria with Czech Academy of Science, and a contact has been established with NIST, USA.
- The work has been presented at international conferences and for BIGCCS partners. In particular, a seminar on CO_2 transport was hosted by GDF SUEZ in Paris in May 2014.

Pulse-echo speed of sound cell at Ruhr-Universität Bochum. (Photo: RUB)

Speed of sound and densimeter setup in new lab at RUB. (Photo: RUB)

Coupled fluid-structure fracture propagation control model

Running-ductile fracture may be compared to what happens to a sausage if you boil it instead of simmering it: It will crack open.

Running-ductile fracture may be compared to what happens to a sausage if you boil it instead of simmering it: It will crack open.

Transport pipelines, be it for natural gas or CO_2, should be designed so that a fracture will not propagate for a long distance. Today, however, nobody can properly predict running-ductile fracture in CO_2 pipelines.

In the past, semi-empirical engineering tools, called two-curve methods, have been developed for safe design and operation of natural-gas pipelines. These tools are not made for newer, high-toughness steels, and particularly not for CO_2, whose properties are distinctly different from those of natural gas.

Indeed, researchers working in the National Grid-led COOLTRANS project in the UK have clearly stated that *the Battelle two-curve method cannot be directly applied to dense phase CO_2 pipelines*[1]. The working hypothesis of BIGCCS Task 2.1 CO_2 pipeline integrity is that inclusion of more physics in the modelling will lead to greater predictive capability.

This has led to a model that is internationally unique due to its combination of advanced fluid and material mechanics – including the two-phase decompression behavior of CO_2. A feature of the model is the direct physical coupling between the fluid and the structure.

The model has been verified for running-ductile fracture experiments in pipelines pressurized with methane and hydrogen, and good results were obtained. However, available data for CO_2 pipelines are very scarce.

The CO_2 Pipetrans II consortium, led by DNV GL, has shown interest for our work and has provided access to data from two medium-scale crack-arrest experiments for pipelines pressurized with CO_2. The first results are expected in 2015.

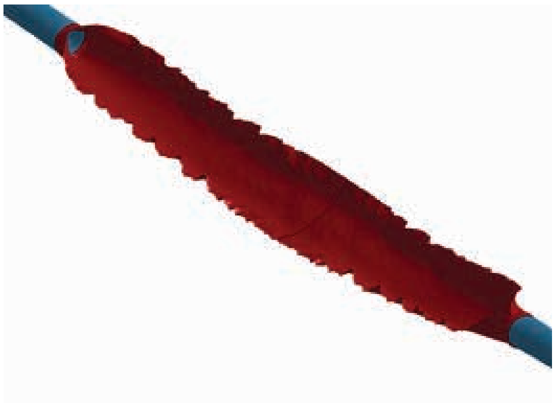


Photo of CO_2Pipetrans II full-scale running-ductile fracture experiment (top) and preliminary calculation. Red arrow in top picture shows position of the initiation crack. (Photo/graphics: SINTEF)

Highly accurate data

CO_2 originating from capture processes will contain various impurities. Even small amounts of such impurities can significantly affect key properties like density, speed of sound, viscosity and the range at which gas and liquid exist at the same time. In two words, this is called thermo-physical properties.

1) Jones, D.G. et al. 2013. Fracture-propagation control in dense-phase CO_2 pipelines. In: 6th International Pipeline Technology Conference. Ostend, Belgium, paper no. S06-02.

For natural gas (which is actually a mixture of several components), meticulous research over many years has resulted in very accurate reference models which can predict the thermophysical properties. For CO_2-rich CCS-relevant mixtures, we do not yet have a reference model.

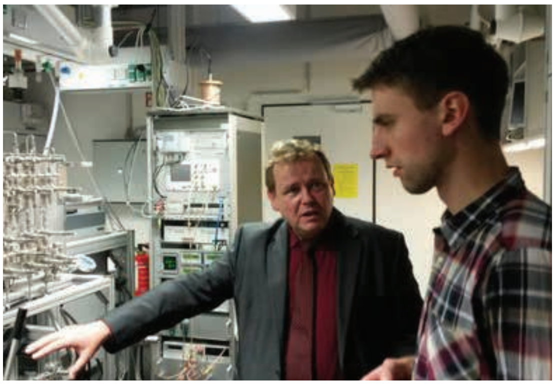
Evidently, accurate models are needed as a reference for engineers who want to perform reliable calculations regarding safe and economic design and operation of CCS systems.

Evidently, accurate models are needed as a reference for engineers who want to perform reliable calculations regarding safe and economic design and operation of CCS systems.

However, not only engineers, but also authorities, should be interested in thermophysical properties. In a future CCS system, the amount of CO_2 will need to be measured, e.g., due to taxation, both at the point of capture and at the storage site. The measurement is indirect, and one has to calculate the amount of CO_2 using the density.

Today's models, however, may yield uncertainties close to 20 % for the density under certain conditions – and that is too high. To build a reference model for thermophysical properties, very accurate measurements over a large range of conditions are needed for quantities such as vapour-liquid equilibrium, density and speed of sound, are needed. This has been the subject of research in Task 2.2 CO_2 mixture properties (CO_2Mix).

The vapour-liquid equilibrium laboratory now generates highly consistent and accurate data which will improve models for transport and conditioning of CO_2-rich mixtures. The set-up draws attention outside BIGCCS, e.g., in the IMPACTS EU FP7 project, in which the CO_2 transport team participates. In 2014, measurements were performed on CO_2-nitrogen mixtures. To obtain data usable for model development, the components have to be investigated in pairs. As there remain large white spots on the research map of the thermophysical properties of CO_2 with impurities, there is enough work for the CO_2Mix vapour-liquid equilibrium laboratory for several years to come.



Prof. Roland Span (RUB) and Dr. Halvor Lund (SINTEF) in the speed-of-sound and density lab at Bochum. Such measurements are an important ingredient in setting up thermophysical property models. (Photo: SINTEF)

The CO_2Mix lab impresses scientific officer Mr. Peter Petrov of the EU Commission. With Mr. Sigmund Størset (left, SINTEF) and Mr. Snorre Westman (right, NTNU). (Photo: SINTEF)

CO_2 Transport Seminar – 21 May 2014

In conjunction with the previous BIGCCS board meeting, a workshop on CO_2 Transport was arranged in Paris. The main topics covered by speakers from SINTEF and GDF SUEZ were pipeline integrity and CO_2 injection in gas fields. Representatives from ConocoPhillips, Gassco, GEUS, Statoil and TOTAL as well as the Research Council of Norway were present. The discussion revealed that some topics investigated with respect to integrity of CO_2-transporting pipelines are also relevant for pipelines transporting rich natural gas.

The CO_2 transport workshop participants.
(Photo: GDF SUEZ)

Innovation and industry benefits

The coupled fluid-structure model for fracture propagation control will, when it is validated, help determining safe pipeline design and operation ranges while reducing the need for full-scale tests, oversizing and installing of mechanical crack arrestors. The potential economical savings are very large. The value of avoiding a large fracture in a CO_2 pipeline close to a populated area in Europe may be even larger.

The potential economical savings are very large. The value of avoiding a large fracture in a CO_2 pipeline close to a populated area in Europe may be even larger.

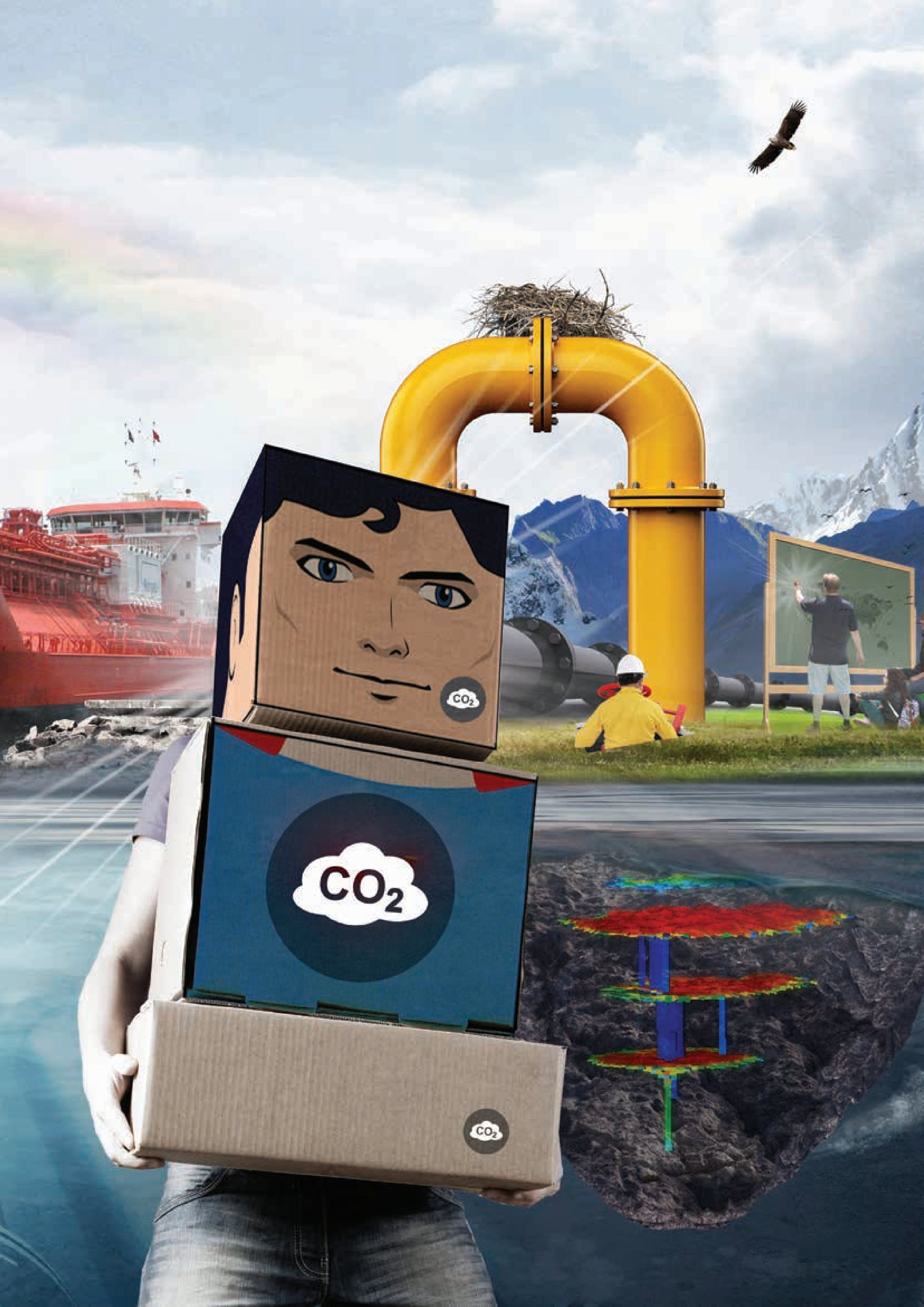
High-quality experimental data are needed to develop high-fidelity thermophysical property models. Such models are, of course, a prerequisite for accurate calculations involving streams of CO_2-rich mixtures. This is obvious for CO_2 transport, but we believe that accurate property models will also be required within other CCS areas where handling of CO_2-rich mixtures is performed.

*** Technology readiness level**

Result	TRL*	Impact
Numerical tool for fracture propagation control in pipelines	3 for CO_2 4 for H_2/CH_4	Ensuring safety and cost-efficiency: 1. Design of new pipelines, 2. New fluids or operating conditions in existing pipelines.
Gravitational preparation of calibration gas	4 to 6	Preparation of gases with an accuracy in composition of the order of 1 ppm in a 10 liter gas cylinder. It can be used for a range of fluids and quantities
CO_2Mix Phase equilibria setup (new) Setup for measurement of density and speed of sound (redesigned for CCS fluids)	4 4	1. Construction and improvement of thermophysical property models for CCS-relevant fluids and conditions. 2. Design of similar setups for other fluids or conditions. 3. Results are needed for realization of CCS systems at all TRLs

Academic achievements

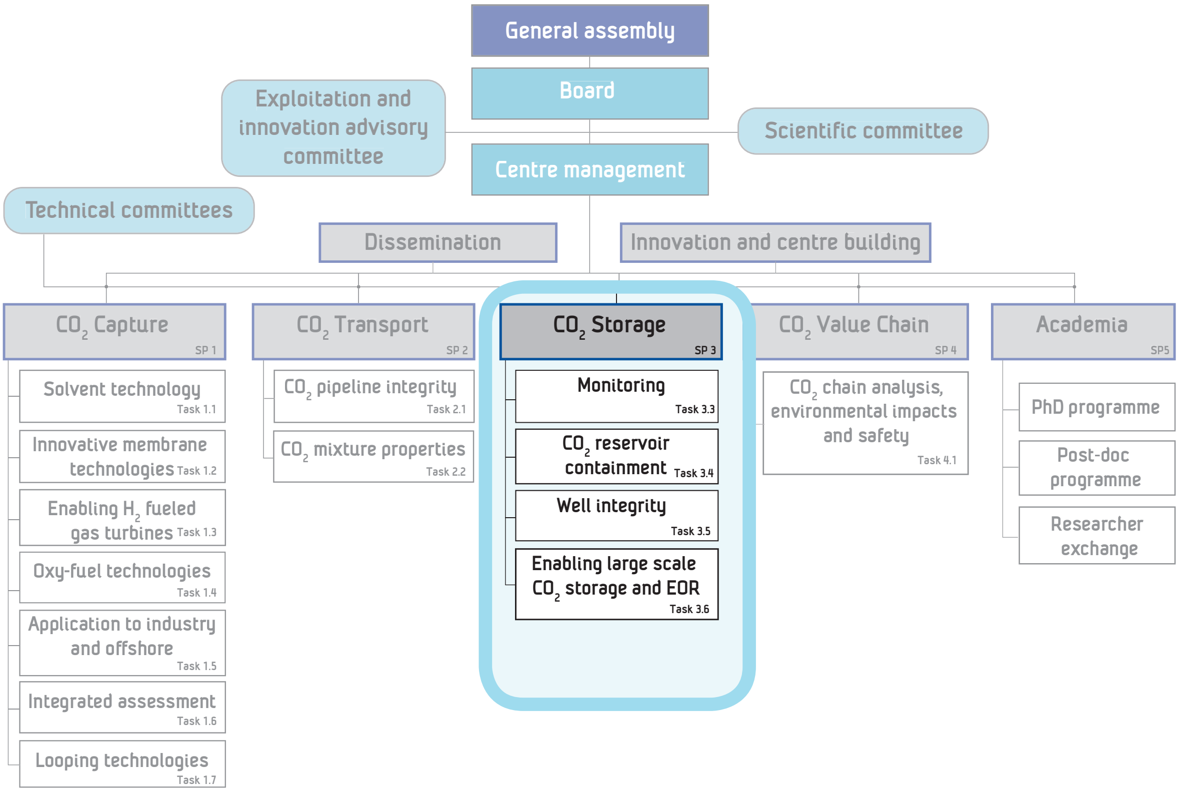
- The PhD candidates of Task 2.2 CO_2 mixture properties have now entered the final phase of their experimental work, and will submit their theses in 2015. Snorre Foss Westman (NTNU) studies gas-liquid equilibria of CO_2-rich mixtures, while Robin Wegge (RUB) studies the density and speed of sound.
- In 2014, our work was presented at two conferences, and three proceedings articles were published. So far, SP2 has published 18 peer-reviewed articles and two popular-science articles.


CO2
CO2
CO2

Grethe Tangen

CO_2 Storage (SP3)

Captured CO_2 must be stored, and BIGCCS SP3 addresses topics critical for long-term underground CO_2 storage. The ambition is to contribute to safe and cost-efficient deployment of large scale CO_2 storage through maximum storage integrity and minimum uncertainty. SP3 also investigates opportunities for value creation, in particular by assessing large scale CO_2 storage combined with enhanced oil recovery (EOR).



Summary of achievements

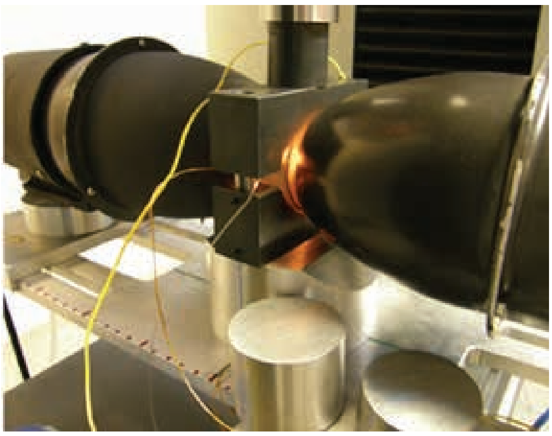
During 2014 the revised organisation of SP3 came into full operation, producing a large number of results from the four tasks:

Monitoring of CO_2:

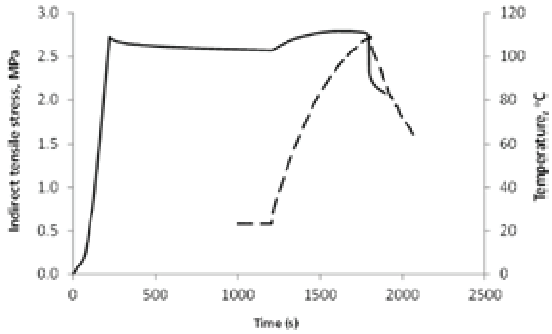
- By using 2D Full Waveform Inversion (FWI) a detailed image of the thin CO_2 layers of the Sleipner CO_2 plume was obtained. First tests using 3D FWI were also successful, clearly showing the CO_2 plume. PhD student Espen B. Raknes developed a first version of 3D elastic FWI and showed promising results when applying the method to real Sleipner data.
- PhD student Sissel Grude and BGS developed and successfully tested two different methods for discrimination between pressure and saturation changes in time-lapse Snøhvit data. The results from the two methods show a clear correlation.
- A new method relying on inversion of seismic and electro-magnetic data was shown to give a reasonably accurate estimate of CO_2 volumes for a synthetic Sleipner model.

Storage integrity:

- A new method was devised to investigate thermal stress related fracturing risk near CO_2 injection wells making routine testing of caprock samples for thermal stress risk easy and quick. Infrared lamps concentrate heat on a caprock shale disk to induce tensile fracturing, thus simulating thermal stress leakage risk in the laboratory.



New set-up with IR lamps heating a shale disc under no deformation boundary conditions. (Photo: SINTEF)



Thermal tensile stress build-up leading to fracturing of the shale.

- To provide input for numerical simulations of fracturing between cement and formation, composite cement and sandstone plugs were tested in compression and direct tension. Surprisingly, failure always occurs first in the sandstone and not at the interface with cement, as postulated in the literature.
- Intermittent CO_2 injection and shut-in cycles can damage the storage site formation due to fatigue loading. Cyclic oil injection was carried out on sandstone cylinder plugs under radial stress close to their strength limit. Permanent deformation of the borehole was measured, but no apparent damage could be observed.
- Alteration of the wettability at the rock-fluid interface may decrease the capillary entry pressure of CO_2 and thereby reduce the sealing integrity of the cap-rock. An apparatus was built to investigate changes of the wettability by measuring the CO_2 entry pressure as a function of time in the presence of brine at reservoir conditions. The entry pressure was lowered when shale was exposed to aqueous CO_2.
- Chemical alterations due to exposure of CO_2 can make sealing caprock more permeable and in the long run, create leakage. An efficient routine was developed, observing crushed shale samples in a µCT as a function of time and CO_2 exposure. For some of the

minerals in the shale specimens chemical changes had occurred.

The integrity of CO_2 wells:

- Micro computed tomography (μ-CT) has been used to study the bonding of well cement to various rock types. When poor bonding (microannuli) was observed, the leakage paths were digitalized and used as input for flow calculations. The numerical calculations of leakage through microannuli were verified by experimental measurements (core flooding of composite rock-cement cores). See figure 1.
- Detailed scanning electron microscopy (SEM) and X-ray tomography studies revealed that cement tends to de-bond/fracture in a weak region near interfaces (instead of at the interfaces). This region also displays higher porosity and permeability than bulk cement. Numerical simulations indicate that the weak zone seems to appear due to non-optimal packing of large cement grains near solid walls. See figure 2.
- Numerical simulations show how downscaled well sections (rock, cement and casing) are affected by downhole temperature variations. Idealized samples with defect-free cement sheaths and more realistic samples are studied. Poor casing centralization and cement defects seems to reduce the well's resistance towards thermal cycling.
- Models are developed for calculating heat transfer in wells and vertical CO_2 flow during injection. The heat transfer model has been experimentally verified, and is used to assess candidate annular sealant materials for use in CO_2 injection wells.

Enabling large-scale storage of CO_2:

- A study conducted by FMEs BIGCCS and SUCCESS in 2013 concluded that there are no technical showstoppers to large scale CO_2 storage on the Norwegian shelf as the industry and research community together possess the required methods and knowledge for qualification of a large-scale storage site. To support the development of large scale CCS, the FMEs in 2014 proposed to validate the current knowledge base through a set of case studies The pre-project was supported by Gassnova.

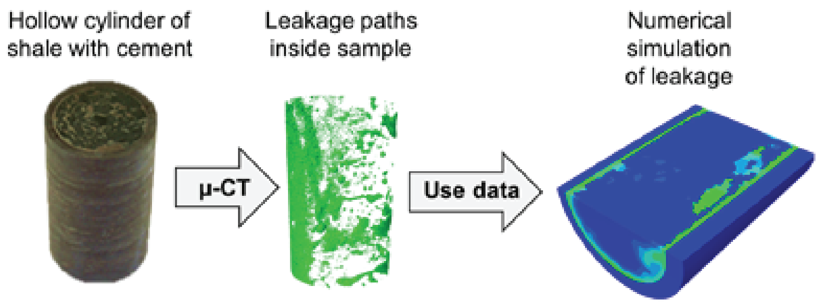


Figure 1.

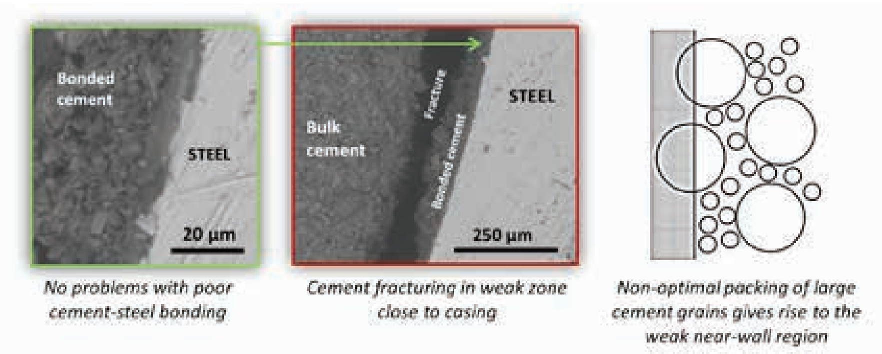
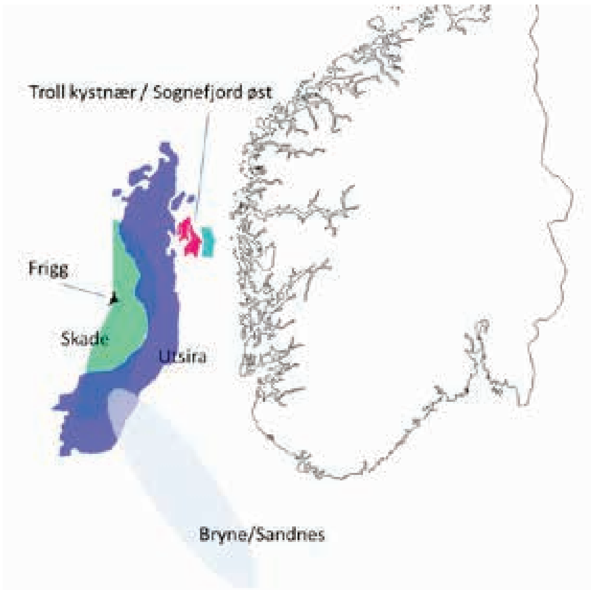
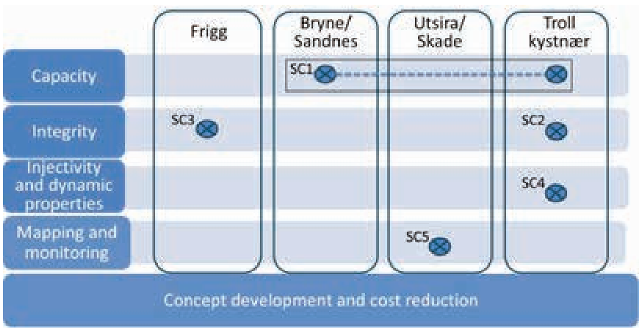


Figure 2.



Location of storage sites selected for case studies



Five case studies (SC) plus concept development is proposed

- CO_2 injection into a formation will result in pore-pressure increase in the connected pore volume. This may cause loss of injection capacity and caprock integrity if the pore pressure exceeds the fracturation or fault reactivation thresholds. Borehole data for the Bunter Sandstone aquifer is reviewed to improve the estimate for fault reactivation pressure and reservoir simulations on the same aquifer are conducted to investigate optimal operation of water extraction wells to limit the pressure increase.
- The increased storage capacity when water extraction is employed depends on several parameters. Effects of reservoir thickness, well-to-well distance and well perforation length have been studied using simulations in a generic reservoir model.
- The BIGCCS value chain model includes options both for aquifer storage and for enhanced oil recovery (EOR). In 2014 the CO_2 EOR module was improved by using results from an earlier project. The new version includes modelling of the variable need of fresh CO_2 as the injected CO_2 breaks through in the production wells.

Hightlights

Strong international collaboration

British Geological Survey (BGS) and Geological Survey of Denmark and Greenland (GEUS) have actively participated in SP3 during 2014. A main focus of BGS was the spectral decomposition method used for pressure and saturation discrimination, and the development of a first automated methodology for quantitative detection of CO_2 leakage. GEUS completed a paper on seismic time-lapse analysis of saturation and pressure response to CO_2 injection, summarizing their contribution to the task in the previous years.

GEUS also participated in work on physical and chemical variations during CO_2 flooding of sandstone samples: an experimental campaign was carried out to investigate the effect of CO_2 exposure on the mechanical strength of sandstone samples. Sandstone specimens were flushed with CO_2 by GEUS, using a WAG scheme. The specimens were then scratch tested by SINTEF to look for strength changes. The close collaboration between BGS, GEUS and SINTEF on injectivity, fracturing and fault reactivation has continued.

During 2014, a collaboration with Lawrence Livermore National Laboratory (LLNL, USA) was established on well integrity. Susan Carroll (LLNL) visited Trondheim in September and participated at the BIGCCS Storage Day. Malin Torsæter (SINTEF) returned the visit in December.

(This text was first presented on the #SINTEFenergy-blog):
http://blog.sintefenergy.com/en

Avoiding leakage from wells – the key to safe CO_2 storage
Blogger Malin Torsæter works at SINTEF Petroleum.

Malin Torsæter

Are you interested in saving our climate by enabling large-scale Carbon Capture and Storage (CCS)? Then you are (believe it or not) also interested in advancing today's well technology and well integrity. Why? Because wells are the "gatekeepers" of stored CO_2! Their quality will determine for how long CO_2 remains imprisoned in deep subsurface reservoirs.

... wells are the "gate-keepers" of stored CO_2!

What is a well?
It is common to visualize wells as just long tunnels into the ground whose sole purpose is to suck up oil and gas from subsurface reservoirs. The fact is, however, that these are complex engineering structures that require careful design – and they are important for so many other purposes than just extracting hydrocarbons. For starters, drilling a well is the only way to get up samples from the subsurface that scientists can study to learn more about our planet. Wells are also essential for exploiting geothermal energy – and (as you will see) for CO_2 storage in the subsurface.

When drilling down into the ground, for whatever purpose, it will become increasingly hot and pressurized with depth. An oil/gas well can have temperatures and pressures similar to those obtained in a kitchen pressure boiler. Thus, the further you drill – the harder it becomes to stabilize the rock walls to avoid collapse. As a result, it is necessary to cement steel pipes into the borehole to "save progress" whenever a difficult rock interval has been pierced. Thus, a typical well ends up with a "telescopic" structure of cemented pipes of different diameters.

When the productive life of a well is over it will be necessary to plug it, since it *can never be removed*. This process typically involves pulling out sections of the steel pipes, and placing cement plugs (of about 100 m length) in two or three intervals of the well. The goal is then that this plugging procedure seals off the reservoir for *eternity*.

Wells in CO_2 storage projects
When it comes to CO_2 storage, wells are used for CO_2 injection purposes and for producing reservoir fluids (to ensure that injection doesn't increase the pressure too much). If CO_2 is to be stored in a depleted hydrocarbon reservoir it must also be expected that a high number of plugged oil/gas wells perforate the site. If these are very old it is important to check the quality of plugging, since early methods for sealing wells involved filling them with tree stumps, logs, animal carcasses and mud.

In principle, all well types can cause leakage of CO_2 – as they represent man-made punctuations of the natural reservoir seal. In fact, the Intergovernmental Panel on Climate Change (IPCC) write in their special report on CCS that: *"injection wells and abandoned wells have been identified as one of the most probable leakage pathways for CO_2 storage projects"* (p. 244).

Contrary to what you might think – this IPCC conclusion is actually great news for all those hoping for large-scale CCS in the future. Why? Because leakage along wells is just so much easier to detect, avoid and mitigate than leakage through other potential pathways, e.g. geological faults. We typically know where the wells are, meaning that limited monitoring is needed to reveal leakage, and we have methods to repair them. The most cost-efficient option is, however, to construct wells in a robust manner to ensure that leakage does not become an issue.

Ongoing research in BIGCCS

Applying wells for large-scale CCS purposes represent a brand new challenge, and it is not given that just adopting well technology from the oil and gas industry will result in the most efficient CO_2 wells. Scientific studies are needed to investigate how to build robust wells for CCS, how to operate them safely – and how to best repair them if they are damaged. This is the focus of the Well Integrity research team, that I am a part of, in BIGCCS.

Through laboratory work and numerical simulations, the Well Integrity team exposes small-scale wells to severe CCS conditions. We then observe how they fail – and recommend strategies for how to avoid and repair such failure. Our team started the work in 2013, but we have already obtained some interesting results. We have mapped how various drilling muds affect cement bonding in CO_2 wells, and we have studied numerically how temperature variations in the well can cause cement damage and subsequent leakage.

In the continuation of our work, we hope to accelerate the deployment of large-scale CCS by developing materials and methods for ensuring safe and cost-efficient CO_2 well integrity.

The most cost-efficient option is, however, to construct wells in a robust manner to ensure that leakage does not become an issue.

SINTEF scientist Malin Torsæter is using micro computed tomography to investigate the interior of a sample consisting of cement and rock. (Photo: Thor Nielsen/SINTEF)

Our team started the work in 2013, but we have already obtained some interesting results.

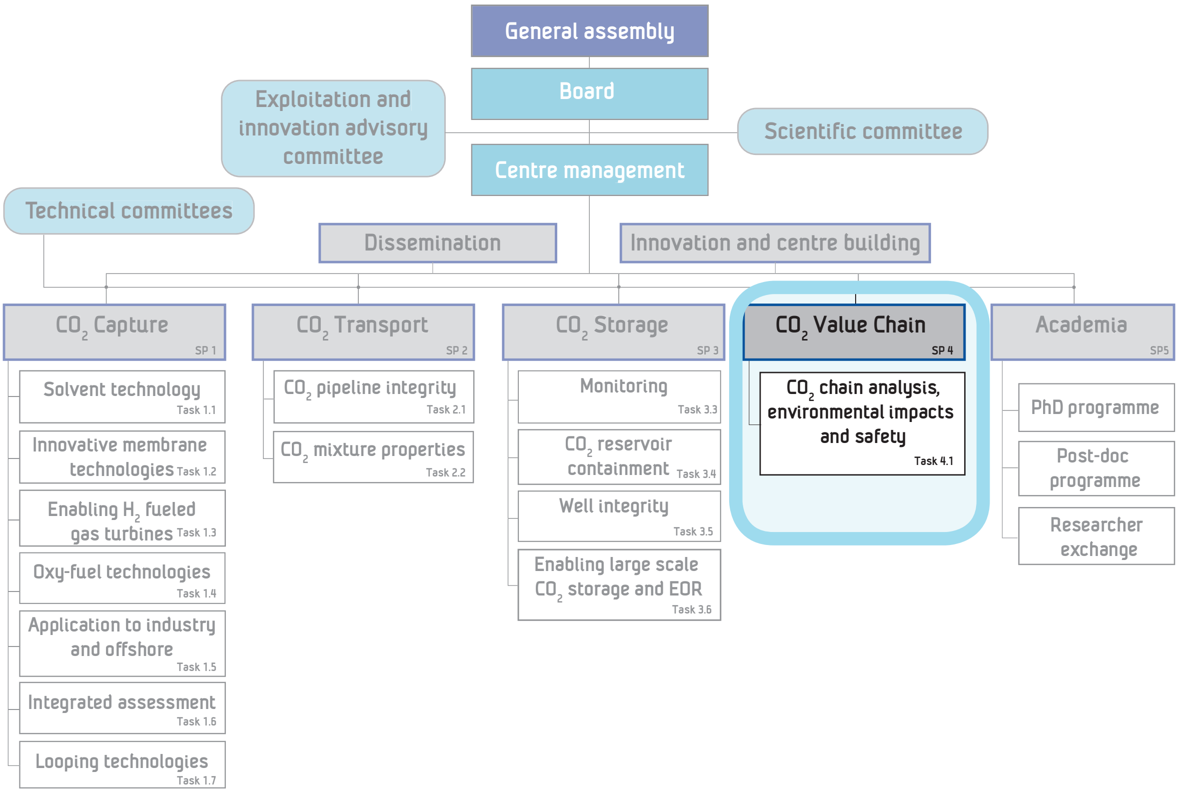
Innovation and industry benefits

*** Technology readiness level**

Innovation	TRL*	Impact
Methodology for CO_2 quantification based on Controlled Source ElectroMagnetics (CSEM) and Full Waveform Inversion (FWI)	3	A new methodology is developed and tested on data obtained from a synthetic Sleipner model. If the technology is demonstrated in a relevant environment (using real data collected at Sleipner), it would become an important tool for monitoring of CO_2 storage, with both operators and service companies being potential users.
Method for assessing thermal tensile strength of caprock	5	An adaptation of the simple Brazilian indirect tensile test to measure thermal tensile stress development in caprock samples to assess thermal fracturing risk and give guidelines on safe temperature ranges for CO_2 injection wells. The method can be used as a simple routine test in the approval of selected storage sites in terms of injection plan, so as to ensure safe storage with minimum leakage risk. The user of the innovation would be either storage permit holders are perhaps preferably accredited laboratories in charge of site approval for the regulatory authorities.
Method for numerical prediction of well leakage	4	A method for calculating leakage through wells if 3D information can be gathered on the leakage paths present in them. this method could form the basis of a software tool (e.g. a "Leakage predictor") that operators and service companies could use to calculate the probability of leakage through wells based on various known input parameters (cement type, mud type, rock type, well operation history).
Stability analysis for diffusion-driven convection	3	Stability analysis for diffusion-driven convection in aquifers with CO_2 storage that improves the theoretical basis for understanding storage safety on the long term, and improved estimates of the time scale related to onset of the convection. Can be important for the evaluation and selection of storage sites as it can be used to check the accuracy of numerical simulations that considers diffusion-driven convection.

Academic achievements

- PhD student Sissel Grude defended her thesis on geophysical monitoring in October 2014. PhD student Espen B. Raknes continued his development of elastic FWI and plan to finish in August 2015. In total, Task 3.3 produced 12 publications during 2014.
- In 2014 also PhD student Mansour Soroush defended his thesis on different phenomena in CO_2 storage in saline squifers and PhD student Szczepan Polak defended his thesis: Laboratory and Numerical Study of Scaling Parameters Used in Modelling of CO_2 Storage in Rocks
- PhD student Dawid Szewczyk: effect of shale saturation investigated on the seismic attributes, with unique laboratory set-up, capable of simulating seismic waves. This can be used to calibrate seismic monitoring, usually using simpler wave velocity models.
- Master student in drilling engineering Gutlug Jafarzade from NTNU contributed to the work on the cement-formation bonding.
- Master student Jørgen Stausland contributed to the work on the generic model simulations of CO_2 injection with water production.


General assembly
Board
Exploitation and innovation advisory committee
Scientific committee
Centre management
Technical committees
Dissemination
Innovation and centre building
CO_2 Capture SP 1
Solvent technology Task 1.1
Innovative membrane technologies Task 1.2
Enabling H_2 fueled gas turbines Task 1.3
Oxy-fuel technologies Task 1.4
Application to industry and offshore Task 1.5
Integrated assessment Task 1.6
Looping technologies Task 1.7
CO_2 Transport SP 2
CO_2 pipeline integrity Task 2.1
CO_2 mixture properties Task 2.2
CO_2 Storage SP 3
Monitoring Task 3.3
CO_2 reservoir containment Task 3.4
Well integrity Task 3.5
Enabling large scale CO_2 storage and EOR Task 3.6
CO_2 Value Chain SP 4
CO_2 chain analysis, environmental impacts and safety Task 4.1
Academia SP5
PhD programme
Post-doc programme
Researcher exchange

Jana Poplsteinova Jakobsen

CO_2 Value Chain (SP4)

CCS chains are case and scenario sensitive, and each case often requires individual design for reaching the optimal solution. The main objective is to develop a consistent and transparent methodology and simulation tool for integrated techno-economic and environmental CCS chain assessment. The ambition is to enable selection of the most promising alternatives for CO_2 chains and reduce uncertainty by improving knowledge and by developing adequate solutions for managing risk in CCS.

Summary of achievements

Specific achievements from the CO_2 Value Chain Sub-Programme include

- BIGCCS SP4 has developed a comprehensive and consistent methodology and a flexible and transparent simulation tool which can be used to:
  - evaluation of CCS chain on several levels: chain components, actor/owner, global chain
  - parameter sensitivity studies (technical, economic, global parameters)
  - further implementation of new modules and additional criteria within the existing framework
- BIGCCS SP4 has performed critical and consistent evaluations of the chain component modules with respect to multiple techno-economic and environmental criteria and illustrated their functionalities on several illustrative case studies.
- The BIGCCS industrial partners have expressed interest for the simulation tool and an activity dedicated to cooperation with Total on techno--economic assessment of CO_2 capture technologies is planned for 2015
- The work in SP4 has also contributed to establishing links with other leading groups internationally. A new project has been established on CO_2 value chain with Czech Technical University in Prague (CVUT) and Energy Research Institute in Czech republic (UJV Rez). In addition, after a workshop with Carnegie Mellon University and the National Energy Technology Laboratory, an activity and publication on membrane is planned with Carnegie Mellon University in 2015.
- The work has been presented at international conferences and for BIGCCS partners. In particular, a workshop on CO_2 value chain was hosted by GDF SUEZ in Paris in May 2014. Representatives from GDF SUEZ, Statoil and TOTAL were present.

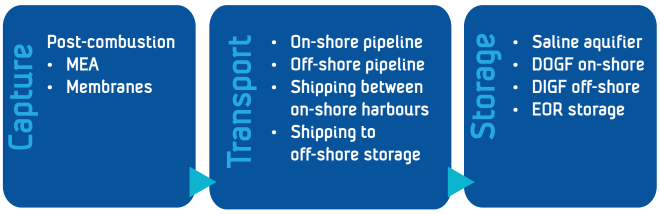


Figure 1: The module library development status.

The Paris SP4 workshop participants.
(Photo: Simon Roussanaly)

TOPICS	Reference
Methodology	[1],[2]
Scenario development	[18]
Relative effects of CCS technology improvement and global marked economic parameters	[19]
Infrastructure ownership	[20]
Impact of CO_2 concentration on capture costs	[3],[4]
Optimal CO_2 capture plant capacity for fluctuating power production	[5],[6]
Methods for improved membrane capture system design	[7],[8],[9],[10]
Effects of the choice of capture technology	[8],[9],[11],[12],[13]
Transport technology selection and associated issues	[14],[15],[16]
Effects of the choice of storage and EOR valuation issues	[12],[17]

Figure 2: Overview of case studies performed within the BIGCCS value chain framework.

Highlights

New systematic methodology for the design and optimization of gas membrane separation processes

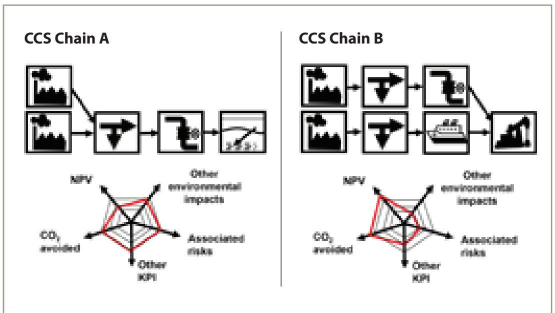
Although membrane processes are conceptually very simple, in practice, complicated membrane process configurations are often employed to meet the product purity and capture ratio constraints while minimizing the cost of CO_2 capture of such membrane systems.

In 2014, SP4 Task 4.1 and SP1 Task 1.5 have together developed a systematic methodology for the design and optimization of gas membrane separation processes based on integrated techno-economic approach.

Attainable Region approach has been developed in order to easily design a cost-optimal multi-stage membrane separation system for given membrane properties.

In addition of being useful for the design of multi-stage membrane process for CO_2 capture from exhaust flue gases (as done in the case of cement and coal in 2014), this methodology can be used to identify specific membrane properties required for membrane systems to be cost-competitive with solvent CO_2 capture.

These results which will be evaluated in 2015 will guide the development of membrane materials for cost-effective CO_2 capture, as well as help the industry to select membranes that can compete with solvent-based capture systems.



Innovation and industry benefits

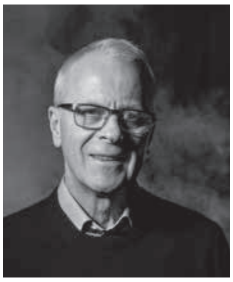
BIGCCS value chain has developed a methodology and tool for integrated multi-criteria assessment of CCS value chain: The iCCS tool (TRL level 5). The comprehensive and consistent methodology and tool developed under SP4 is of particular interest for:

- Potential CCS infrastructure owners and or customers as it enables selecting the most cost-effective options for CCS deployment;
- Technology providers and engineering companies as it will highlight the needs for technology improvements and measures to promote the CCS technology;
- Policy and decision makers as the tool could be used to assess the effects of alternative policy and global market scenarios on the CCS chain economy;

The tool development was illustrated and documented through several case studies. It is planned to share this tool with the BIGCCS industrial partners so that they can use it internally within their organizations. This is expected to lead to constructive comments and suggestions for further development and improvements. The tool will continue to be further developed, improved, and extended by SINTEF Energy Research and it will be used in other projects to evaluate and compare various CCS chain options.

Academic achievements

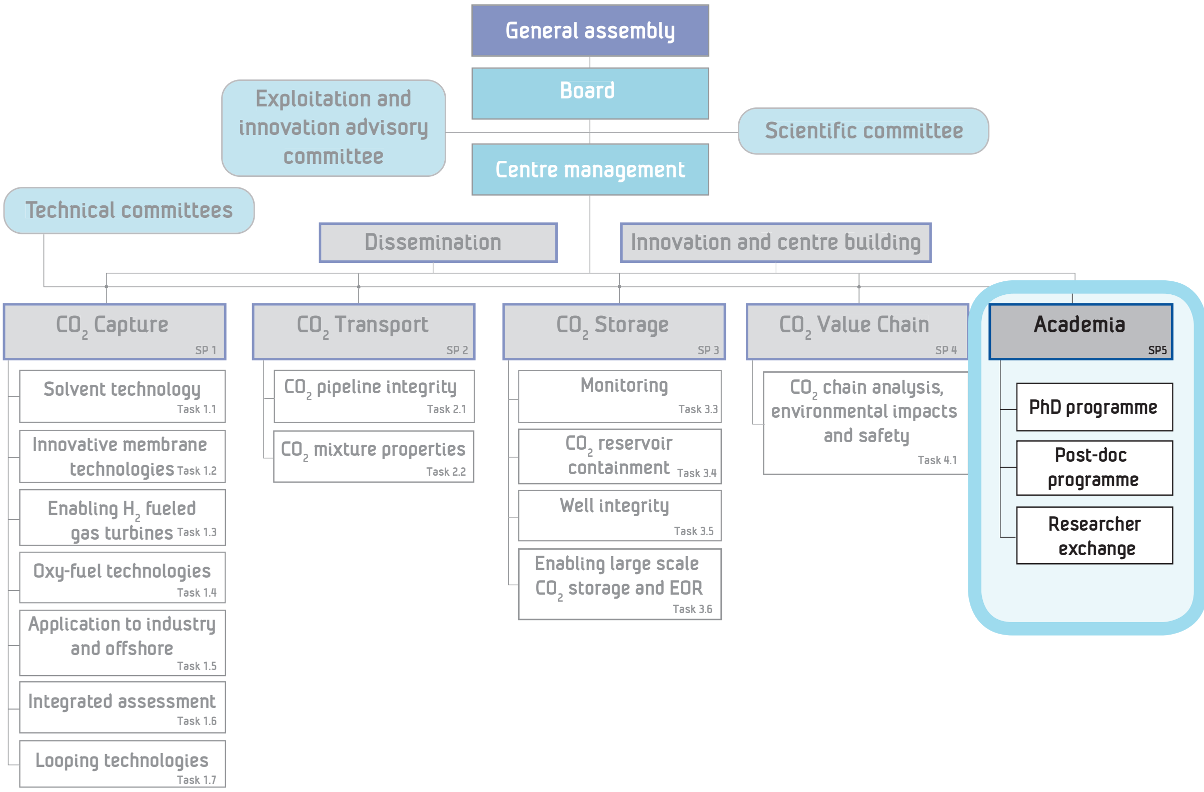
- In 2014, our work was presented at GHGT-12 conference: 3 papers were presented (2 oral presentations and 1 poster presentation)
- In 2014, journal paper on benchmarking of CO_2 transport technologies has been published in Int. J. of Greenhouse Gas Control, and a paper on low-temperature CO_2 capture with CO_2 transport and storage has been submitted to Applied Energy
- So far, SP4 has published 13 articles since 2009



Truls Gundersen

Academia and recruitment (SP5)

2014 was an extremely busy year, and nine PhDs successfully defended their theses.



The original recruitment objective for BIGCCS was to produce 18 PhDs and eight Post-doc candidates, a total of 26 researchers. These numbers have increased somewhat thanks to a number of added premium projects (KPNs). The total work force (past and current) can now be summarized as follows (as of 31 December 2014):

- 30 candidates are active or have completed, two more will be recruited in 2015
- 13 PhDs have completed (three from Norway, two from USA, two from Iran, two from China, and one from Poland, France, Germany and Argentina)
- Six Post.docs have completed (three from Iran, two from China, and one from Bangladesh)
- 10 currently active PhDs and one active Post.doc
- Eight of the 30 candidates are females
- 23 of the 30 candidates are (or have been) at NTNU
- Two candidates at University of Oslo
- Two candidates at University of California, Berkeley, USA
- Two candidates at Technical University of Munich, Germany
- One candidate at Ruhr University Bochum, Germany

2014 was an extremely busy year, and nine PhDs successfully defended their theses.

Among the 19 completed candidates our records show that five have been recruited by NTNU, three by Statoil, two by University of Oslo, one by SINTEF, one by Aker Solutions, one by FEI Trondheim, one by Petroleum Geo Services, one by Siemens (USA), one by Nevada Automotive Test Center (USA), and one by Chinese Academy of Science (Beijing).

PhDs completed in 2014

Georg Baumgartner

Rafael Antinio Sànchez

Vajiheh Nafisi

Szczepan Piotr Polak

Camilla K. Vigen

Sissel Grude

Einar Vøllestad

Xiaoguang Ma

Mansour Soroush

International cooperation

International cooperation is a central and integral part of the BIGCCS activities. Through the participation of strong European industry partners and highly ranked international R&D providers, the BIGCCS Centre maintains a high international profile.

(Photo: Shutterstock)

Seven nations are currently represented, including the industrial participants: *ConocoPhillips* (USA/Norway), *Gassco (Norway)*, *GDF SUEZ* (France/Norway), *TOTAL* (France/Norway), *Shell* (Netherlands/Norway), Statoil (Norway) and the research institutes *DLR* (Germany), *TUM* (Germany), *GEUS* (Denmark), and *BGS* (UK).

The partners play active roles within the various research tasks, and as members of the different BIGCCS committees.

In addition, several BIGCCS research groups work in close collaboration with researchers from other international research institutes and universities. The partners play active roles within the various research tasks, and as members of the different BIGCCS committees.

Cooperation with international research groups outside BIGCCS

BIGCCS continues cooperation with:

- *University of Berkley* (California, USA) and Professor Robert Dibble. University of Berkley is one of the world leading research groups on combustion.
- The *Combustion Research Facility at Sandia National Laboratory,* USA, which is the U.S. Department of Energy's premier site for research in combustion technology.
- *Ruhr Universität Bochum* and Professor Roland Span. This research group is among the highest ranking in the field of characterization of thermophysical properties of fluids, including- CO_2 and CO_2 mixtures.

- *Nordic CCS Research Centre* (NORDICCS). This is first and foremost a networking collaboration between R&D institutes and the industry in the Nordic countries with focus on CCS deployment.
- *European Carbon Dioxide Capture and Storage Laboratory Infrastructure* (ECCSEL). The ECCSEL mission is to develop a European distributed, integrated research infrastructure, involving the construction and updating of research facilities.
- *The Impact of the Quality of CO_2 on Transport and Storage Behaviour* (IMPACTS). A FP7 project led by SINTEF that will close critical knowledge gaps related to transport and storage.

Cooperation with international organizations
BIGCCS personnel are actively participating in activities spearheaded by the following international organizations:
- International Energy Agency
- The European Energy Research Alliance (EERA)
- Global CCS Institute (Australia)
- National Institute of Advanced Industrial Science and Technology (Japan)
- CORIA-Université de Rouen (France)
- Corning S.A. (France)
- Air Liquide (France)
- SGU (Sweden)
- TNO (the Netherlands)
- IFP (France)
- Colorado School of Mines (USA)
- Freie Universität Berlin (Germany)
- Saint Gobain (France)
- Princeton University (USA)
- Mälardalen University (Sweden)
- University of North Dakota (USA)

Through the last amended KPN projects we also cooperate with:
- North Carolina State University
- RWTH Aachen University
- Georgia Tech
- Brigham Young University
- National Renewable Energy Lab
- Stanford University

The partners play active roles within the various research tasks, and as members of the different BIGCCS committees.

Organization of conferences, workshops and seminars
BIGCCS is the organizer of *the Trondheim CCS Conference series.* The next Conference will be held June 16-18, 2015. Following the success of TCCS-6 (2011) and TCCS-7 (2013), both with more than 400 participants, 150 oral presentations and 100 posters, it is interesting to note that the number of abstracts received for TCCS-8 is at an all-time high – more than 300. More information about TCCS-8 can be found here: **http://www.sintef.no/tccs-8**

From TCCS-7 plenum session, June, 2013. *(Photo: SINTEF)*

Communication and dissemination

BIGCCS seeks to be a source for objective information on research and development, status and potentials of CCS at several levels, for the research community, for decision makers, and for the public. Different instruments and communication channels are used for the different target groups. Below are highlighted some of the activities carried out in 2014.

Publications overview
BIGCCS has a strong emphasis on publishing the results from the R&D activities. High-ranking scientific journals are much preferred to reports. The table below gives an overview of the publication figures for the BIGCCS Centre in 2014. Figures are extracted from the Cristin database

Publication type	2014
Part of book, reports	3
Conference and scientific presentations	36
Information material	3
Report/thesis	10
Journal publications	38
TOTAL	**90**

Publication figures from Cristin.no

Publication/communication channels

Web
A new BIGCCS web (**www.bigccs.no**) was launched in 2014. Format and readability is improved and the layout also accommodates tablets and smartphones. The webpage provides open information from the Centre in a popular science fashion, including updated information on publications and relevant events. Statistics show that the new web more than doubled the number of views during the last seven months in 2014 (from below 500 per month to over 1100 on monthly average) after the web was launched in May.

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www.BIGCCS.no

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2014					424	1035	517	986	974	1388	1633	1208	8165

Number of web views per month. The new web was launched in May 2014.

Blog

A blog was added as a new feature to the webpage in 2014, and the blog entries are also published on the newly launched #SINTEFenergy blog. The intention with the blog is to allow researchers to communicate research results from the Centre to a wider audience.

The intention with the blog is to allow researchers to communicate research results from the Centre to a wider audience.

Mona Mølnvik blogged about BIGCCS innovations 22. December.

Newsletter

The BIGCCS Newsletter gives information about the latest Centre developments. Sent to around 400 e-mail addresses around the world, it contains information about research results, publications and events. A new layout and format was introduced in 2014, the main purpose being to shorten the volume of information in the Newsletter itself, and to provide links for further reading. Seven Newsletters were issued in 2014, and the intention is to step up the frequency during 2015.

Technical meetings and Sub-Programme Days

BIGCCS consists of five Sub-Programmes and 14 different research tasks. An important channel of communication and cooperation are the technical meetings. Each research task organises one or two technical meetings per year where plans are made and results are communicated with the industry partners. Typically, such meetings are held via tele-conferences or video meetings. Occasionally, also physical meetings are set up. Sub-Programme Capture and Storage also organized their "Capture Day" and "Storage Day". These are seminars where all partners meet to discuss results and plans, and where also external contributors can be invited.

Consortium Day

The BIGCCS Consortium Day 2014 was held at Scandic Lerkendal, Trondheim on September 23, with more than 50 attendees. The main purpose of the Consortium Day is to display results from the research activities. Sub-Programme leaders gave an overview of status within their domain, and researchers presented selected highlights from the research activities. In addition to the presentations from the BIGCCS research partners, invited presentations were given by: Dr. Susan Carrol (Lawrence Livermore National Laboratory, USA), Mr. Ole Kristian Sollie (Shell), and Dr. Åse Slagtern (Research Council of Norway). Dr. Carrol gave an overview of the carbon storage activities in the US, while Mr. Sollie shared with the audience some of Shell's thoughts on CCS.

Conferences

International Conference on Greenhouse Gas Technologies (GHGT)

The biggest CCS conference world-wide is the bi-annual GHGT series, typically with more than 1000 attendees. BIGCCS has attended the last conferences with a significant number of

BIGCCS Consortium Day at Lerkendal Stadium, September 23, 2014. *(Photo: SINTEF)*

researchers. At GHGT-12, held in Austin, Texas in November 2014, BIGCCS contributed nine oral and nine poster presentations. At the conference, BIGCCS board member, Professor Hallvard Svendsen was given the prestigious *Greenman Award* for his long-lasting efforts in the field of CCS.

Trondheim Conference on CO_2 Capture Transport and Storage (TCCS)

The BIGCCS Centre receives a high public profile by organising the *Trondheim Conference on CO_2 Capture Transport and Storage (TCCS)*, which has become a major scientific CCS conference. BIGCCS had a central role in organizing the TCCS-6 (2011) and TCCS-7 (2013). The two last conferences had more than 400 participants from over 20 countries, 150 oral presentations and 100 posters. Consequently, the Trondheim Conference is established as one of the leading international, scientific CCS conferences, and building on this success TCCS-8 will be held in June 2015. More information about TCCS-8 can be found here: **http://www.sintef.no/tccs-8**

SINTEF and NTNU CCS Award

SINTEF and NTNU initiated in 2011, *the SINTEF and NTNU CCS Award*, and the second award presented at the TCCS-7 in 2013. The Award is given to individuals for outstanding achievements within the field of carbon capture, transport and storage (CCS), and includes an honorarium of NOK 25,000, a plaque, and free participation at the next TCCS conference.

Award winners so far are Erik Lindeberg, SINTEF (2011) and Tore A. Torp, Statoil (2013). The next winner will be announced at the TCCS-8 conference in June 2015.

The Greenman Award is the highest recognition in the field of CCS. It is given to individuals having contributed significantly to the development of CCS. The award is only given every second year, and is announced at the GHGT Conference.

In 2014 the award was given to Professor and BIGCCS Board member Hallvard Svendsen at the GHGT-12 conference, which was held in Austin, Texas, October 5-9.

In selecting Prof. Svendsen, the jury emphasized his long lasting contributions in the development of amine technology for post-combustion CO_2 capture, his achievements in CO_2 capture education at NTNU, and his successful cooperation with SINTEF and the industry.

BIGCCS premium projects

Nine knowledge-building projects with user involvement (KPN) have so far been amended to the BIGCCS consortium Agreement. These projects typically have a duration of three years and require that industry partners funds at least 20 per cent of the budget.

KPN project	Objective	Related SP	Amended
CO_2 Mixture Properties	Establish, through experimental activities, thermo-physical properties for CO_2 mixtures relevant for CCS	2	2010
Chemical Looping Combustion Phase II	Building on knowledge, results and CLC reactors from BIGCLC Phase I, the world's largest pressurized CLC reactor for gaseous fuels will be established, together with the underpinning research needed to appraise the CLC technology	1	2011
Cross-Atlantic Modelling, Programing and Simulation	Develop the next generation of high-fidelity numerical design tools for CCS-related combustion technologies through a cross-Atlantic collaboration	1	2012
Fundamental effects of CO_2 on rock properties	Improved understanding of the fundamental effects of CO_2 injection on geomechanical and sealing properties of a storage reservoir and the caprock	3	2012
Chemical Looping Combustion Phase III	Bring CLC technology closer to commercialization by achieving 150 kW rig CLC operation using an optimized oxygen carrier in industrial relevant conditions and up-scaling ready	1	2013
Novel hybrid membranes for post-combustion CO_2 capture in power plant and industry	Enable membrane technology to be efficient in combating greenhouse gas emissions by developing innovative membranes	1	2013
Shaping advanced materials	Select materials selective to CO_2 capture from different post and pre-combustion sources and shape them into usable structures (particles, monoliths) for different sorption processes	1	2014
Ensuring well integrity during CO_2 injection	Enable safe CO_2 injection through improved under-standing of leak development as a function of time, injection scheme and downhole materials	3	2014
Uncertainty reduction in monitoring methods for improved CO_2 quantity estimation	Develop methods for quantification and reduction of uncertainties in CO_2 monitoring	3	2014

Health, safety and environment (HSE)

As host institution, SINTEF Energy Research conducts all its projects in line with NORSOK Standard S-006, "HSE Evaluation of Contractors", and the Consortium Agreement commits the partners to use HSE regulations in line with the NORSOK Standard. This includes a stringent evaluation of criteria and guidelines of environmental impacts of activities.

The Consortium Agreement requires all partners to report immediately and without undue delay to the host institution any accidents, incidents or near misses in connection with BIGCCS activities. This issue is dealt with at each Board meeting. All BIGCCS meetings have HSE as the first agenda item.

SINTEF uses SYNERGI as an integral part of its systematic HSE work. This is a web-based system where all employees can report any kind of accidents, near misses, observations, dangerous conditions, non-conformance, and improvement proposals. Each BIGCCS CMG meeting starts with a discussion of such reports and conditions that should have been reported.

During 2014 four HSE reports were registered related to BIGCCS activities, none of which resulted in injuries to personnel:

- **Dangerous condition:** Mercury leakage outside laboratory. A triple-point cell was leaking a small volume of mercury upon arrival after calibration. A few droplets were spilt on the ground outside the lab. All procedures for handling the incident were adhered to. A professional company was called to handle the leakage. No harm was done, and all mercury spill was recovered.
- **Dangerous condition:** Insufficient air-flow in hoods. A routine check revealed insufficient air-flow in some hoods. This did not apply to hoods used for BIGCCS work. The work stations with hoods in question were closed and repaired, before work could commence.
- **Dangerous condition:** Lead-foil discovered in laboratory. A routine assessment revealed that lead-foil was used. The substance was not registered. The condition was registered in SYNERGI and risk evaluation was carried out in EcoOnline. Disposal took place in a proper manner. Lead-foil will no longer be used in the lab.
- **Incident:** Barrier on a CO_2 bottle was broken. CO_2 was seeping out of the bottle. No injury was reported. There was adequate ventilation in the room. The leakage was shut off immediately when discovered. The incident was registered in SYNERGI and followed up by the laboratory manager.

SINTEF Materials and Chemistry was in 2014 certified by IQNet and Nemco AS for R&D activities within material technology, advanced materials and nanotechnology, applied chemistry and bio technology, oil and gas, and green energy and process industry. Certificates were obtained for: Environmental Management Systems (ISO 14001:2004), Occupational Health and Safety Management System (SN-BS OHSAS 18001:2007), and Quality Management System (ISO 9001:2008).

2014 is the first year SINTEF reports no sick-leave caused by work-related accidents. This encouraging result will be followed up with a new campaign in 2015 where all SINTEF employees will have to attend a HSE course related to all kinds of daily activities. This includes laboratory activities, fieldwork, and HSE during travelling.

People

NAME	AFFILIATION	DEGREE	SEX	POSITION
BIGCCS Management				
Mona J. Mølnvik	SINTEF ER	PhD	F	Research director
Nils A. Røkke	SINTEF ER	PhD	M	Vice-president
Centre Management Team				
Anne Steenstrup-Duch	SINTEF ER	MA	F	Communication Manager
Rune Aarlien	SINTEF ER	PhD	M	Centre Manager
Jon Magne Johansen	SINTEF ER	MSc	M	Operations Manager
CO_2 Capture (SP1)				
Andrea Gruber	SINTEF ER	PhD	M	Senior research scientist
Anna Lind	SINTEF MC	PhD	F	Research scientist
Annett Thøgersen	SINTEF MC	PhD	F	Research scientist
Aud I Spjelkavik	SINTEF MC	BSc	F	Senior engineer
Bjørnar Arstad	SINTEF MC	PhD	M	Senior research scientist
Geir Haugen	SINTEF MC	MSc	M	Research scientist
Hanne Kvamsdal	SINTEF MC	PhD	F	Senior research scientist
Hugo Jakobsen	NTNU	PhD	M	Professor
Håkon Ottar Nordhagen	SINTEF MC	PhD	M	Research scientist
Inge Saanum	SINTEF ER	PhD	M	Research scientist
Inna Kim	SINTEF MC	PhD	F	Research scientist
Jonathan Polfus	SINTEF MC	PhD	M	Research scientist
Kari Anne Andreassen	SINTEF MC	BSc	F	Senior engineer
Karl Anders Hoff	SINTEF MC	PhD	M	Senior scientist
Kjell Wiik	NTNU	PhD	M	Professor
Knut Thorshaug	SINTEF MC	PhD	M	Senior research scientist
Kristin Jordal	SINTEF ER	PhD	F	Research scientist
Marie-Laure Fontaine	SINTEF MC	PhD	F	Senior research scientist
Mario Ditaranto	SINTEF ER	PhD	M	Research manager
Martin Fleissner Sundin	SINTEF MC	PhD	M	Research scientist
Mehdi Pishahang	SINTEF MC	PhD	M	Research scientist
Nils Erland L. Haugen	SINTEF ER	PhD	M	Research scientist
Ove Darell	SINTEF MC	BSc	M	Engineer
Partow P. Henriksen	SINTEF MC	PhD	F	Research director
Rahul Anantharaman	SINTEF ER	PhD	M	Research scientist
Richard Blom	SINTEF MC	PhD	M	Research director
Sigurd Sannan	SINTEF ER	PhD	M	Research scientist
Thijs Peters	SINTEF MC	PhD	M	Senior scientist
Thor Mejdell	SINTEF MC	PhD	M	Senior research scientist
Tommy Mokkelbost	SINTEF MC	PhD	M	Senior research scientist
Truls Nordby	UiO	PhD	M	Professor
Ugochukwu Edvin Aronu	SINTEF MC	PhD	M	Research scientist

Vincent Thoreton	NTNU	PhD	M	Post Doc
Wen Xing	SINTEF MC	PhD	M	Research scientist
Yngve Larring	SINTEF MC	PhD	M	Senior research scientist
Yuanwei Zhang	NTNU	MSc	M	Student
Øyvind Langørgen	SINTEF ER	PhD	M	Research scientist

CO_2 Transport (SP2)				
Anders Austegard	SINTEF ER	Dr.ing.	M	Research scientist
Eskil Aursand	SINTEF ER	MSc	M	Master of Science
H. G. Jacob Stang	SINTEF ER	Dr.Ing.	M	Research scientist
Håkon O. Nordhagen	SINTEF MC	PhD	M	Research scientist
Markus Richter	RUB	Dr.Ing.	M	Postdoc
Morten Hammer	SINTEF ER	PhD	M	Research scientist
Ingrid Snustad	SINTEF ER	MSc	F	Research manager
Roland Span	RUB	Dr.Ing.	M	Professor
Sigmund Ø. Størset	SINTEF ER	MSc	M	Research manager
Sigurd W. Løvseth	SINTEF ER	Dr.Ing.	M	Senior scientist
Stéphane Dumoulin	SINTEF MC	PhD	M	Research scientist
Svend T. Munkejord	SINTEF ER	PhD	M	Chief scientist

CO_2 Storage (SP3)				
Alexandre Lavrov	SINTEF PR	PhD	M	Senior scientist
Alv-Arne Grimstad	SINTEF PR	PhD	M	Senior research scientist
Andy Chadwick	BGS	PhD	M	Team leader CCS
Anna Stroisz	SINTEF PR	PhD	F	Research scientist
Amir Taheri	NTNU	PhD	M	Post.doc
Anouar Romdhane	SINTEF PR	PhD	M	Research scientist
Carsten Nielsen	GEUS	MSc	M	Reservoir engineer
Claus Kjøller	GEUS	PhD	M	Head of laboratory
Dag Wessel-Berg	SINTEF PR	PhD	M	Senior scientist
Erik Lindeberg	SINTEF PR	PhD	M	Chief scientist
Ector Querendez	SINTEF PR	MSc	M	Research Scientist
Gareth Williams	BGS	PhD	M	Geophysicist
Grethe Tangen	SINTEF PR	PhD	F	Senior scientist
Halvor Lund	SINTEF ER	PhD	M	Research scientist
Idar Akervoll	SINTEF PR	MSc	M	Senior scientist
James White	BGS	PhD	M	Geophysicist
Jan Åge Stensen	SINTEF PR	PhD	M	Researcher
Jelena Todorovic	SINTEF PR	PhD	F	Research scientist
John Williams	BGS	BSc	M	Geoscientist
Karen Lyng Anthonsen	GEUS	MSc	F	Geo-engineer
Lars Erik Walle	SINTEF PR	PhD	M	Research scientist
Malin Thorsæter	SINTEF PR	PhD	F	Research scientist
Maria Barrio	SINTEF PR	PhD	F	Senior Business Developer
Peder Eliasson	SINTEF PR	PhD	M	Research manager

Peter Frykman	GEUS	PhD	M	Senior researcher
Pierre Cerasi	SINTEF PR	PhD	M	Research manager
Raheleh Farokhpoor	NTNU	PhD	F	Post.doc
Rasmus Rasmussen	GEUS	PhD	M	Senior advisor
Rob Cuss	BGS	PhD	M	Specialist
Robert Drysdale	SINTEF PR	PhD	M	Senior advisor

CO_2 Value Chain (SP4)				
Amy Brunsvold	SINTEF ER	PhD	F	Research scientist
Jana P. Jakobsen	SINTEF ER	PhD	F	Senior scientist
Erik Skontorp Hognes	SINTEF FA	MSc	M	Research scientist
Simon Roussanaly	SINTEF ER	MSc	M	Research scientist

Academia and recruitment (SP5)				
Børge Arntsen	NTNU	PhD	M	Professor
Christian Thaulow	NTNU	PhD	M	Professor
Hugo A. Jacobsen	NTNU	PhD	M	Professor
Inge R. Gran	NTNU	PhD	M	Adjunct Professor
Ivar Ståle Ertesvåg	NTNU	PhD	M	Professor
Jens-Petter Andreassen	NTNU	PhD	M	Professor
Jon Kleppe	NTNU	PhD	M	Professor
Jyh-Yuan Chen	UC Berkeley	PhD	M	Professor
Magne Hillestad	NTNU	PhD	M	Professor
Martin Landrø	NTNU	PhD	M	Professor
May-Britt Hägg	NTNU	PhD	F	Professor
Olav Bolland	NTNU	PhD	M	Professor
Ole Torsæter	NTNU	PhD	M	Professor
Reidar Haugsrud	UiO	PhD	M	Ass. Professor
Robert W. Dibble	UC Berkeley	PhD	M	Professor
Roland Span	Ruhr Univ. Bochum	Dr.Ing.	M	Professor
Rune Holt	NTNU	PhD	M	Professor
Terese Løvås	NTNU	PhD	F	Professor
Thomas Sattelmayer	Tech. Univ. München	Dr.Ing.	M	Professor
Tor Grande	NTNU	PhD	M	Professor
Truls Gundersen	NTNU	PhD	M	Professor

Visiting researcher

Name	Affiliation	Nationality	Sex	Duration	Topic
Foreigners visiting BIGCCS					
Alan Kerstein	Sandia Natioal Laboratories	USA	M	2 months	Pre-combustion CO_2 capture, hydrogen combustion

BIGCCS researchers abroad

Name	Visiting	Nationality	Sex	Duration	Topic
BIGCCS researchers					
Sigurd Sannan	Sandia National Labs and Univ. Of California Berkeley	Norway	M	1 month	Hydrogen combustion, pre-combustion CO_2 capture
Sigurd Sannan	North Carolina State University	Norway	M	1 month	Hydrogen combustion, pre-combustion CO_2 capture
Andrea Gruber	Sandia National Labs	Italy	M	8 months	Direct numerical simulation of hydrogen-air flame flashback in a duct with fuel-oxidant mixture stratification
Nils Erland Haugen	Stanford University	Norway	M	2 weeks	Oxy-fuel combustion

Post docs with support from BIGCCS

Name	Nationality	Sex	Duration	Topic
Anwar Bhuiyan	Bangladesh	M	2010-2011	Monitoring, Leakage and Remediation
Hassan Karimaie	Iran	M	2010-2012	Storage Behavior
Xiangping Zhang	China	F	2011-2013	CO_2 Value Chain
Nousha Kheradmand	Iran	F	2012-2013	CO_2 Pipeline Integrity
Chao Fu	China	M	2012-2014	Integrated Assessment and Oxy-Combustion
Raheleh Farokhpoor	Iran	F	2012-2014	Effects of CO_2 on Rock Properties

Post docs with support from others

Vincent Thoréton	KPN BIGCLC Phase III	France	M	2014-	Chemical Looping Combustion Technologies

PhDs with support from BIGCCS

Name	Nationality	Sex	Duration	Topic
Alexandre Morin	France	M	2009-2012	Mathematical modelling and numerical simulation of two-phase multi-component flows of CO_2 mixtures in pipes
Andrew North	USA	M	2010-2013	Experimental Investigations of Partially Premixed Hydrogen Combustion in Gas Turbine Environments
Don Frederick	USA	M	2010-2013	Numerical Investigations of a Hydrogen Jet Flame in a Vitiated Coflow
Georg Baumgartner	Germany	M	2010-2014	Experimental Investigation of Hydrogen Flashback Behavior in Turbulent Boundary Layer
Rafael Antinio Sànchez	Argentina	M	2010-2014	Modeling and Simulation of Sorption-enhanced Steam Methane Reforming (SE-SMR) operated in circulating Fluidized Bed Reactors

Vajiheh Nafisi	Iran	F	2010-2014	Development of Mixed Matrix Membranes for Carbon Dioxide Capture
Xinzhi Chen	China	M	2010-2013	Dense Oxygen Separation Membrane Materials – Thermal and Chemical Expansion of La1-xSrxMO3-d (M = Fe, Co) and Tape Casting and Mechanical Properties of La2NiO4+d
Sissel Grude	Norway	F	2010-2014	Geophysical Monitoring of CO_2 Storage in the Subsurface
Einar Vøllestad	Norway	M	2010-2014	Mixed Proton Electron Conducting Oxides as Hydrogen Transport Membranes in Electrochemical Potential Gradients
Xiaoguang Ma	China	M	2010-2014	Precipitation in Carbon Dioxide Capture Processes
Mansour Soroush	Iran	M	2010-2014	Simulation and Experimental Investigation of Different Phenomena in CO_2 Storage in the Saline Aquifers
Rengarajan Soundararajan	India	M	2011-2015	Coal based Power Plants using Oxy-combustion for CO_2 Capture: Process Integration Approach to reduce Capture Penalty
Amir Taheri	Iran	M	2010-	Study of Density-Driven-Natural-Convection (DDNC) Mechanism in CO_2 Sequestration in Heterogeneous and Anisotropic Brine Aquifer
Robin Wegge	Germany	M	2010-	Speed of sound and density measurements of binary, CO_2-rich mixtures over a wide temperature and pressure range
Nina Enaasen	Norway	F	2011-	CO_2 Separation
Espen Birger Raknes	Norway	M	2011-	3D elastic time-lapse full waveform inversion
Marcin Dutka	Poland	M	2012-	Studies of Low NO_x Burner Technology
David Szewczyk	Poland	M	2012-	Rock physics and geomechanical aspects of seismic monitoring of CO_2 storage in the subsurface
Snorre Foss Westman	Norway	M	2013-	Experimental investigation of phase equilibria of CO_2 mixtures relevant for CCS
Sohrab Gheibi	Iran		2013-	Geomechanical Modelling of CO_2 Injection and Storage
Vera Hoferichter	Germany	F	2013-	Experimental Investigations on the Influence of Acoustic Excitations on Flame Flashback during Premixed Hydrogen Combustion in a Model Burner

PhDs with support from others

Szczepan Piotr Polak	$BIGCO_2$	Poland	M	2007-2014	Laboratory and Numerical Study of Scaling Parameters used in Modelling of CO_2 Storage in Rocks
Camilla K. Vigen	University of Oslo	Norway	F	2009-2014	Novel mixed Proton Electron Conductors for Hydrogen Gas Separation Membranes

Master degrees (2010–2014)

Name	Sex	Title	Semester
SP1 - CO_2 Capture			
Helene Østby	F	Dynamic modelling and simulation of a CO_2 capture plant	Spring 2010
Matthieu Dreillard	M	Energy Considerations around an amine CO_2 capture plant	Spring 2010
Birgitte Johannessen	F	Numerica studies of flame propagation in channel flow	Spring 2010
Espen Tjønneland Wefring	M	Nano-structuring of oxygen permeable membrane by chemical etching techniques	Spring 2011
Julia D. Meyer	F	Processing and mech. props. of tape casted films with compositions La0.2Sr0.8Fe0.8Ta0.2O3 as membranes for syngas production	Spring 2011
Jasmin Birkl	F	Implementation and measurements on an exhaust gas analysing system	Spring 2011
Vidar Graff	M	Degydration and compression of contaminated CO_2 rich gas	Spring 2011
June Munkejord	F	CO_2 capture in solutions with simultaneous precipitation of solids	Spring 2011
Stian Tangen	M	On the solution of the pellet and reactor model for SMR process using the methods of weighted residuals	Spring 2011
Simon Bless	M	Study of Cooling Air Injection at Gas Turbine Combustors with Large Eddy Simulation	Fall 2011
Tore Hatleskog Zeiner	M	Process Integration Potentials in Coal-based Power Plants	Fall 2011
Runar Bøen	M	An experimental investigation of co-sintering of oxygen permeable asymmetric membranes with compositions La0.2Sr0.8Fe0.8Ta0.2O3	Spring 2012
Petter Wibe	M	Optimisation of strength and permeability of tape castred poous sub-strates with composition La0.2Sr0.8Fe0.8Ta0.2O3	Spring 2012
Nils Wagner	M	Stability and permeation properties of asymmetric La0.2Sr0.8Fe0.8Ta0.2O3 membranes for syngas production	Spring 2012
Balbina Hampel	F	Measurement of the Air Excess Ratio of an Auto-Igniting Flame by Means of Spectroscopy	Spring 2012
Dan Lagergren	M	Oxygen permation in optimized, asymmertric LSFAl membrane for syn-gas production	Fall 2012
Henriette Næss	F	New process configurations for post-combustion CO_2 removal	Spring 2013
Hilde Bråtveit Ekrheim	F	Modeling and model identification of an equilibrium amine system - MEA and MDEA	Spring 2013
Frank Arne Glimastad	M	Ceramic materials for oxygen separation membranes	Spring 2013
Silje Kathrin Nesdali	F	Development of novel oxides for use in O_2 permeable membranes	Spring 2013
Belma Talic	F	Oxygen permation in optimized, asymmertric ceramic membranes for syngas production	Spring 2013
Kjartan Juul Skarbø	M	Operation study of low No_x burner technology	Spring 2013
Nicolai Austarheim	M	DNS simulations of acoustic instabilities in low emission combustion systems	Spring 2013
Mohammad Ostadi	M	Surrogatye Models for Integrated Reforming CC Optimization	Spring 2013
Tobias Hummer	M	3D conjugate heat transfer analysis of engine cylinder heads	Fall 2013
Elisabeth Børde	F	CO_2 Capture from cement production	Spring 2014
Kine Hammersland	F	Energy considerations around an amine CO_2 capture plant	Spring 2014

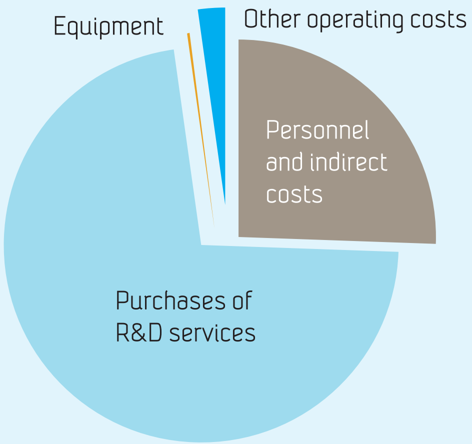
	SP2 - CO_2 Transport			
28	Nicolas Morin	M	Coupled fluid-structure model used for modelling of running fracture in ductile steel pipelines	Fall 2010
29	Gjermund Haug	M	Running fracture in a H_2 pressurized pipeline: From small scale material testing to full scale experiments and simulations	Spring 2011
30	Steffen Valheim	M	Running fracture in a H_2 pressurized pipeline: Characterization and simulation of dynamic ductile fracture in two X65 pipeline steels	Spring 2011
31	Alexander Maurer	M	Commissioning of a single-sinker densimeter and first measurements in CO_2 rich binary mixtures	Spring 2014

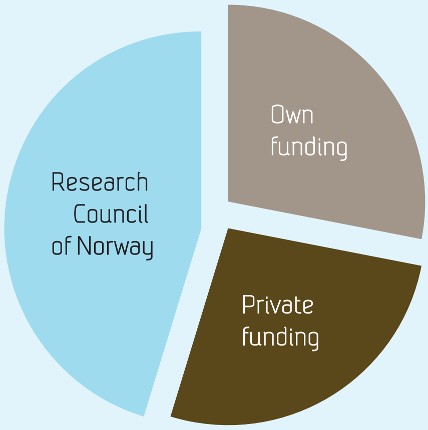
	SP3 - CO_2 Storage			
32	Alberto Perez Garcia	M	Capture, transport and storage of CO_2. Storage cap. study in Spain	Spring 2010
33	Sissel Grude	F	Sea bed diffractions and impact on 4D seismic data	Spring 2010
34	Tone Trudeng	F	Sensitivity analysis on the detctability of fractures on 2-D seismic: An early warning of CO_2 leakage	Spring 2010
35	Alexander Eilertsen	M	Dissolution of CO_2 in aquifer due to natural convection	Spring 2011
36	Edyta Haziak	F	Theoretical considerations of CO_2 storage capacity in aquifers	Spring 2011
37	Thibaut Forest	M	CO_2 as enhanced oil recovery method	Spring 2012
38	Hanne Halvorsen	F	Mapping of shallow tunnel valleys combining 2D and 3D seismic data	Spring 2012
39	Ole Eiesland	M	Estimating sea bed velocities from normal modes	Spring 2012
40	Erik Andreas Westergaard	M	Stability analysis of CO_2 - brine immiscible flow in homogeneous core samples	Spring 2013
41	Quentin P. J. Pallotta	M	Study of non-local equilibrium options in reservoir simulation	Spring 2013
42	Hendrik Andre Westervold	M	Evaluation and comparison of various miscible CO_2-EOR methods	Spring 2014
43	Jørgen Stausland	M	Generating a regression model proxy for CO_2 storage	Spring 2014

Financial statement

Actual costs	NOK
Personnel and indirect costs	11 402 574
Purchases of R&D services	31 943 181
Equipment	26 143
Other operating costs	904 531
Total	**44 276 429**

Funding	NOK
Own funding	12 484 174
Private funding	11 792 255
Research Council of Norway	20 000 000
Total	**44 276 429**





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2. **Lavrov, Alexandre; Larsen, Idar; Holt, Rune Martin; Bauer, Andreas; Pradhan, Srutarshi.** Hybrid FEM/DEM simulation of hydraulic fracturing in naturally-fractured reservoirs. I: *48th US Rock Mechanics/Geomechanics Symposium Proceedings*. American Rock Mechanics Association (ARMA) 2014 ISBN 978-0-9894844-1-1. s. -. SINTEFPETR
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5. **Arstad, Bjørnar; Lind, Anna Maria; Andreassen, Kari Anne; Joanna, Pierchala; Thorshaug, Knut; Blom, Richard.** In-situ XRD studies of dolomite based CO_2 sorbents. GHGT-12; 2014-10-05 - 2014-10-09. SINTEF
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