BIGCCS

International CCS Research Centre

Annual Report 2015

FME
CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH
The Research Council of Norway

What a year we have had!

What a year we have had! I always try to remind people that we are in the middle of an energy and climate revolution. It's happening as I write and you read this message.

We need transitional management now. The energy sector is where the printed media sector was 10 years ago. Some figure out the "zeitgeist" of what is happening and manage to help shape the new reality and business models, whereas those who remain in denial lose.

You might say that jobs are at stake but we also see the emergence of a new renewable industry that will provide good jobs. It is clear that many processes used by the industrial sector cannot take place without creating emissions, which makes CCS a useful and viable solution. This is particularly true for cement, steel, aluminium and fertilizers, and has become a new focus for CCS technology. It's about the European capacity and capability to produce.

The same applies to carbon-negative solutions, where we bring down the stock of CO_2 in the atmosphere. This was a favourite card to play during the Conference of the Parties meeting in Paris in December (COP21). The models showed that a massive roll out of carbon-negative solutions was critical to achieving the 2-degree target, not to mention the 1.5-degree target that we are now striving to make. In this case, we are talking about more than 10 gigatonnes of biogenic CO_2 being stored in the years beyond 2050.

CCS is thus in great demand for all fuels and sectors including the bioeconomy and the circular economy. We also see that various regions are taking different stances on CCS, especially with respect to their choices of fuels and sectors. So who will take the challenge and shape the future? I hope that we can take part in showing new possibilities.

Our centre has been a strong supporter of the idea of carbon-neutral natural gas, and more recently we have become intrigued by the re-emergence of combining natural gas with hydrogen production, export and storage of CO_2. At least we can then be sure that there will be prospects for long-term markets.

You might say that jobs are at stake but we also see the emergence of a new renewable industry that will provide good jobs.

Unfortunately, the countries of the world are still behaving as if we have oceans of time to act, when we in practice have almost no time to mitigate global warming. The COP21 agreement was important, but the difficult part comes now – we must act. The Norwegian Centres for Environment-friendly Energy research address this need to act. BIGCCS is a vital part of the toolbox and we hope the spirit and the DNA of BIGCCS will continue in a new centre under the FME programme. There is no time to lose; we have high expectations for what CCS can do for the planet. With our distinguished partners I am confident we can and will make a difference in combating global warming.

Chairman of the Board

Dr. Nils A. Røkke

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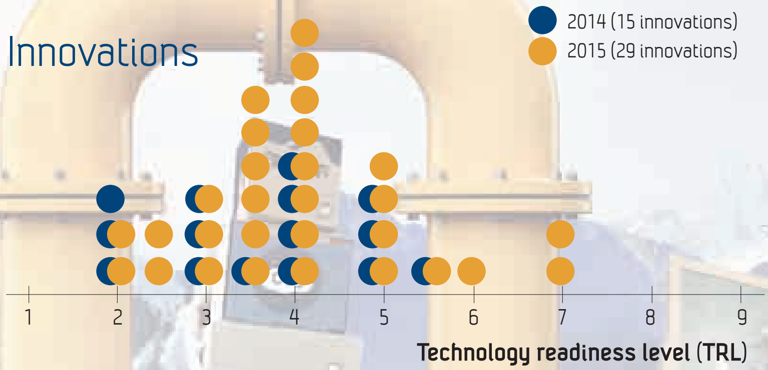
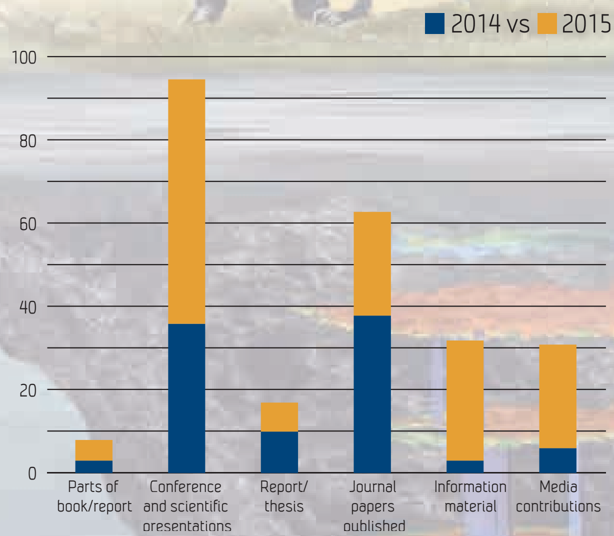
2015 in numbers

Innovations

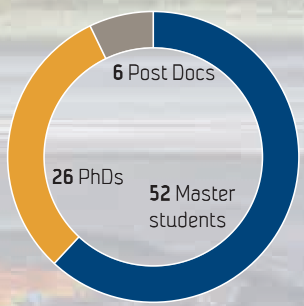


Publication and dissemination



Education

2009–2015



Contents

Message from the Director

2015 is the 7th year in operation for *BIGCCS – International CCS Research Centre* that has grown to a powerful centre of excellence; both in terms of the number of people involved and the results produced. This was evidenced during the 8th *Trondheim Conference on CO_2 Capture, Transport and Storage* (TCCS-8) that was held in June. The conference was organized by BIGCCS under auspices of NTNU and SINTEF with 350 participants whereof 185 from abroad, strong industry participation and a renewed momentum in the CCS discussions. BIGCCS contributed with 15 oral presentations and 12 posters, and the achievements was summarized in the TCCS publication *BIGCCS Innovations – Measures to Accelerate CCS Deployment.*

Further, the BIGCCS Consortium Day containing technical meetings, poster sessions, General Assembly as well as the Climit-BIGCCS PhD seminar was a great success. All together 30 innovations were presented and discussed during the technical meetings and the poster sessions. The dialogue between experts representing BIGCCS industry partners, researchers, PhD students, professors and representatives from the Climit program taking place during these days, gives renewed motivation, and relevance to the 2016 strategies and work plans.

2015 has been a very productive year for the educational program led by Professor Truls Gundersen, NTNU. Five PhD students defended their thesis in 2015. In total, 26 of the PhDs and postdocs have now completed their work, all with results contributing to the acceleration of the implementation of CCS.

During 2015, the concept study for the *Norwegian full-scale CCS project* was of great interest for BIGCCS since the issues being discussed in the Norwegian full-scale project are linked to the research areas of BIGCCS. It has been interesting and motivating to note the relevance of the research topics in BIGCCS.

In addition to innovations and education, BIGCCS is also expected to deliver publications, both as highly ranked journal papers as well as popular science. BIGCCS has recorded 563 publications in the Cristin database all together. In 2015, 25 journal papers, 59 conference and scientific presentations, 15 blogs, 8 newsletters, 25 media contributions.

As this annual report shows, the international cooperation with origin in BIGCCS is substantial. In 2015, three Horizon 2020 CCS projects were started, all with strong links to BIGCCS. The projects are Gateway and CEMCAP (hosted by SINTEF), and ECCSEL (hosted by NTNU).

By this I would like to thank the large BIGCCS team for the efforts to address real barriers to CCS, hence the contribution to full-scale CCS deployment.

Mona J. 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 full effects of the CO_2 Storage (SP3) reorganization were seen in 2015 and showed that the restructuring has been a success

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.

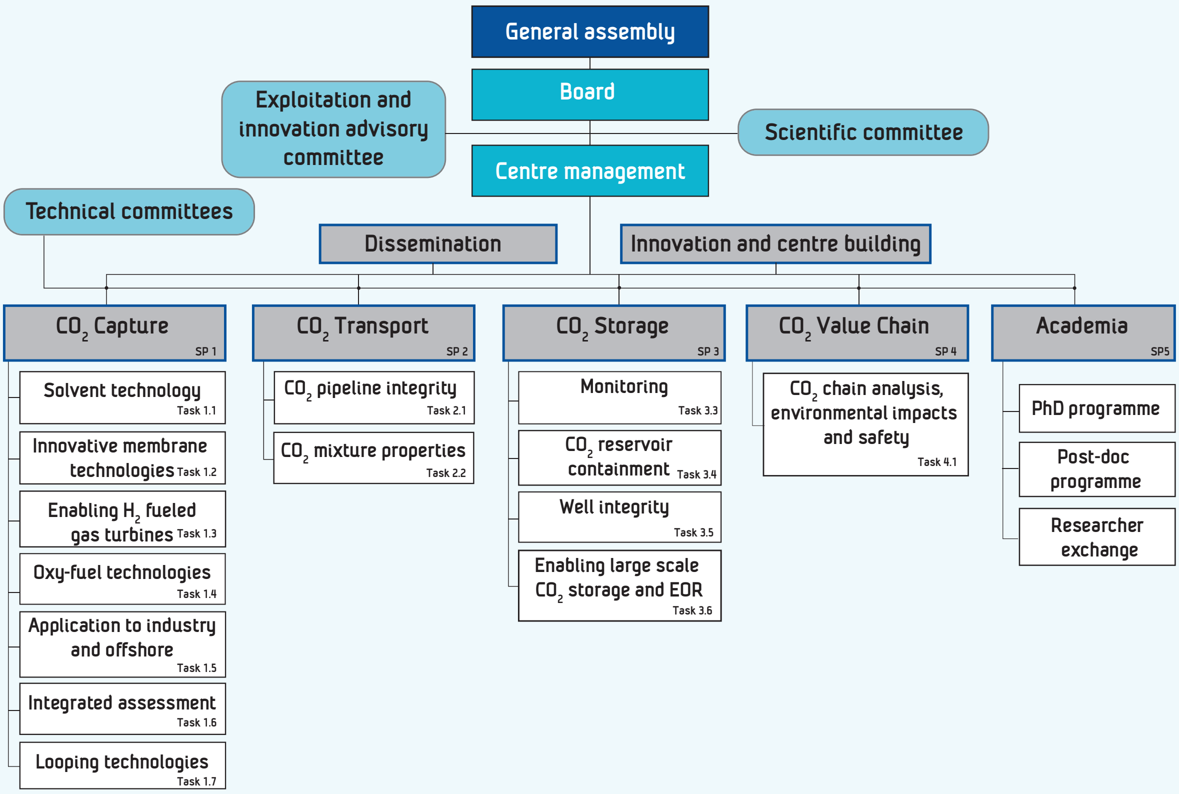
In CO_2 transport, the combination of theories and models describing pipeline fracture resistance and CO_2 fluid dynamics requires a coupled analysis of the problem. Different numerical simulation methods are used and will create improved understanding of the two-way influence between the CO_2 fluid 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 2015 meeting in Trondheim on September 23. Mr. Ole Kristian Sollie (Shell) is the Chairman of the GA.

The Board is the operative decision-making body of the Centre. One Board meetings was held in 2015; on May 20 (Bygnes, Norway). A meeting was also scheduled for December 8, but this one was postponed to January 6, 2016. Members of the Board in 2015 were: Dr. Rune Bredesen (SINTEF), Mr. Peter Britze (GEUS), Dr. Per Ivar Karstad (Statoil), Mr. Ole Kristian Sollie (Shell), Mr. Tom Steinskog (Engie), Mr. Gudmundur Kristjansson (Gassco), Prof. Olav Bolland / Hallvard Svendsen (NTNU), and Dr. Rune Teigland (TOTAL). Chairman of the Board is Dr. Nils A. Røkke (SINTEF).

The Scientific Committee is an advisory committee with leading international academics giving guidance to the Centre related to scientific progress. The committee 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).

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

Board meeting at Bygnes, May 20. From left: Remi Dreux (Engie), Tom Steinskog (Engie), Jana P. Jakobsen (SINTEF), Åse Slagtern (Research Council of Norway), Britta Paasch (Statoil), Nils A. Røkke (SINTEF), Mona J. Mølnvik (SINTEF), Ole Kristian Sollie (Shell), Rune Bredesen (SINTEF), Arve Erga (TOTAL), Peter Frykman (GEUS), Svein Solvang (Gassco) and Hallvard Svendsen (NTNU).

Work breakdown structure

BIGCCS consists of five Sub-Programs; 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 bottom half 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 was to have a more clear research profile, prioritise scientific topics where the team is strong and innovation potentials are identified, and increase the focus on enhanced oil recovery (EOR) as an opportunity for making a business case in CO_2 storage. New tasks were added while others 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.

The full effects of the SP3 reorganization were seen in 2015 and showed that the restructuring has been a success. Some of the benefits are: closer interaction with research partners within each task, more collaboration between tasks and SPs in the centre, the PhD students are participating more actively in SP3 meetings, and more industry response to proposals and presentations. In addition, the international cooperation is strengthened and the collaboration with FME SUCCESS has continued through Task 3.6 participation in Gassnova project "Large scale CO_2 storage".

Partners

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

Industry parties:

- Gassco
- Engie
- Shell Technology Norway
- Statoil
- TOTAL E&P

Research institutes:

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

Susan Carroll (Lawrence Livermore National Laboratory) in lively conversation with SP3 Manager Grethe Tangen (SINTEF).

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 in *technical meetings*. Typically, each task organize two technical meetings per year.

The Centre organizes an annual *Consortium Day*. At this event all partners and researchers are invited, and the objective is to provide a snapshot of last years' activities and results. The Consortium Day 2015 was held at Royal Garden Hotel, Trondheim on September 22-23, with more than 40 attendees. The focus of the meeting was results and innovations from the research activities and potential "take-aways" for the industry partners. A particularly successful part of the event was the poster sessions. BIGCCS researchers had produced more than 30 posters, which generated substantial interest from the industry partners.

Consortium Day 2015 at Royal Garden Hotel on September 22-23.

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 22 meetings during 2015. 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.

The focus of the meeting was results and innovations from the research activities and potential "take-aways" for the industry partners.

As a way of disseminating results from the Centre, and to spur discussions BIGCCS will offer a series of webinars during the spring of 2016. This is a service to BIGCCS partners only. Planning began in 2015, and the first webinar will be held early April 2016. An updated webinar program can be found on the BIGCCS webpage.

Ole Torsæter,
PhD Supervisor
BIGCCS, Department of Petroleum Engineering and Applied Geophysics, NTNU.

"Researchers at Department of Petroleum Engineering and Applied Geophysics (IPT) have since early 1980s investigated the possibility of using CO_2 injection for enhanced oil recovery (EOR).These studies both on master and PhD level were mainly field scale numerical simulations based on CO_2-modified hydrocarbon-rock interaction parameters and limited CO_2 fluid parameters.

The BIGCCS program made it possible to start studies on micro scale, core scale, reservoir segment scale and full reservoir scale within all of our relevant subject areas; reservoir engineering, petrophysics, geomechanics and geophysics. IPT was involved in projects on CO_2 injection in aquifers before BIGCCS, like the Sleipner project, but the increased activity due to BIGCCS resulted in more student interest, which resulted in employing an Adjunct Professor dedicated to CO_2 storage technology and a new master course titled; CO_2 Storage: Operation and Integrity of Engineered CO_2 Storage. BIGCCS has also been important for our participation in research projects with European partners and now lately IPT has developed a research and educational cooperation with the University of Calgary on CO_2 storage."

... but the increased activity due to BIGCCS resulted in more student interest

Sissel Grude,
BIGCCS PhD student 2010–2014

"In the period 2010-2014, I conducted my PhD at NTNU with funding from the BIGCCS project. My thesis was on geophysical monitoring of CO_2 injected to the underground. Being part of a large project opened many doors for me in my doctorate work. Project meetings, internal conferences and meetings with industrial partners gave me a network in the CO_2 industry. I got the opportunity to work with and learn from, and publish results with other experienced researchers in the project. The BIGCCS project gave me a better understanding of the entire CO_2 chain, not just in the "storage part" that I was part of.

After I completed my doctorate, I started working for Statoil. My work as field geophysicist in Statoil entails injection and production of oil and gas, and geophysical monitoring of the reservoir. This has many analogues to injection of CO_2, where one needs an understanding of fluid migration and pressure variation in the reservoir. My doctorate in BIGCCS made me well prepared for independent work in my discipline and the interdisciplinary work that is typical working in the industry."

"Being a partner in BIGCCS has given me the feeling of belonging to a very important CCS community. All major aspects of CCS has been dealt with and combined with high competence research it has given us a very valuable and useful increase in knowledge to contribute to TOTAL's policy to be an active actor in the reduction of GHG emissions."

Arve Erga,
Research & Development,
Production Technology Lead,
TOTAL E&P NORGE AS

Being a partner in BIGCCS has given me the feeling of belonging to a very important CCS community.

"The FME scheme (Centres for Environment-friendly Energy) began in 2009 as a direct result of the parliamentary Climate Agreement Act in 2008. The centres undertake concentrated, focused and long-term research at a high international level in order to solve specific challenges in energy and environment.

BIGCCS has focused on CO_2 capture, transport and storage. In addition, value chain analysis has been a central part of the research. BIGCCS has been important for competence development in CO_2 management for both research actors and for industrial companies, particularly through educating a significant number of PhD candidates.

BIGCCS has a broad commitment within several CO_2 capture technologies, and benchmarking of immature processes has been part of the work. Important fundamental research is carried out in transport of CO_2 mixtures and challenges related to rupture of transportation pipelines. Within storage, important investigations are undertaken to ensure safe storage of CO_2 and the potential for large-scale storage of CO_2 on the Norwegian Shelf.

BIGCCS has contributed to a broad and coordinated effort in CO_2 handling through expansion of activities and integration of spin-off projects to its portfolio with new CLIMIT projects (the Norwegian RD&D program for the development of technology for CO_2 management), as well as industry-supported projects. BIGCCS has been very important for Norway's strong international position in research on CO_2 management."

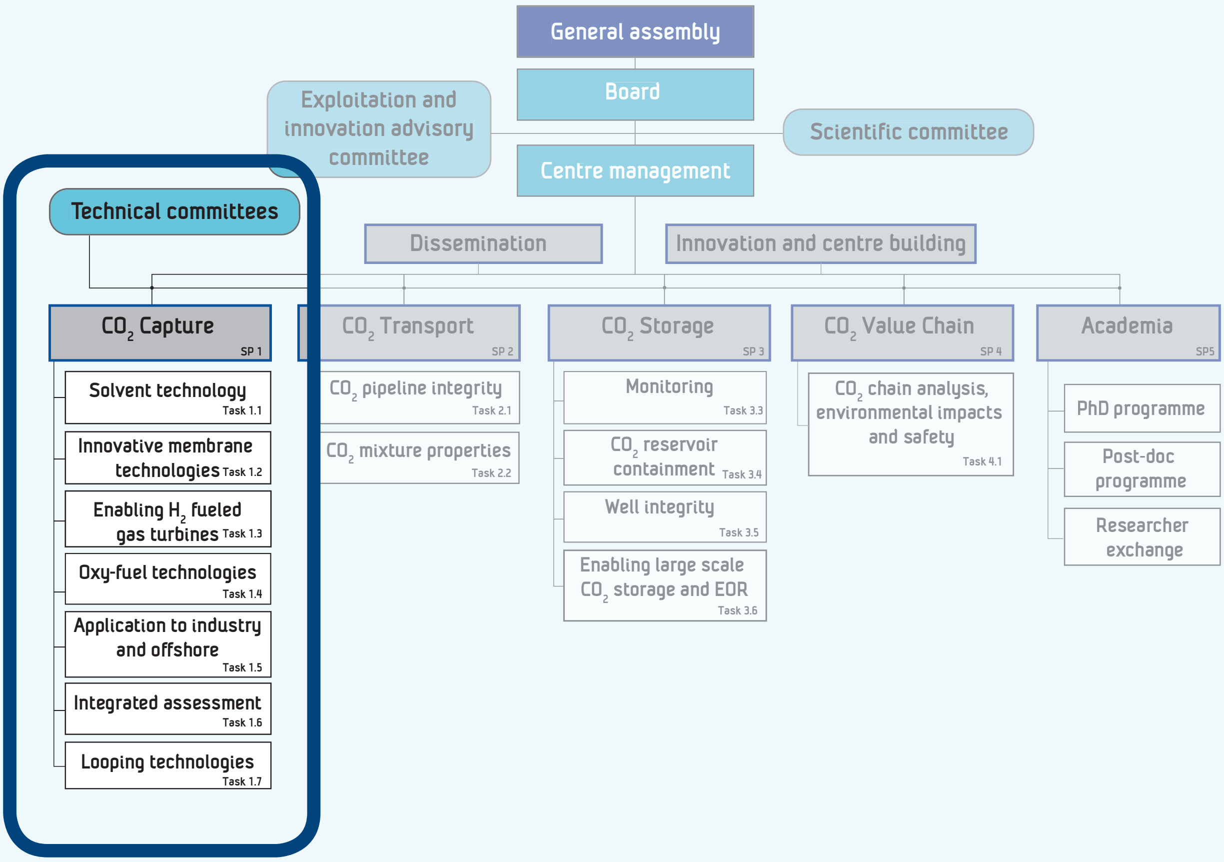
Åse Slagtern,
Special Advisor,
Research Council of Norway

Partow Pakdel Henriksen

CO_2 capture (SP1)

CO_2 is generated by combustion of any fuel consisting carbon and from various industrial sources. Capture of CO_2 takes place before or after combustion.

The overall aim is to reduce CO_2 emissions from being released into the atmosphere. SP1 studies number of technologies to capture CO_2.

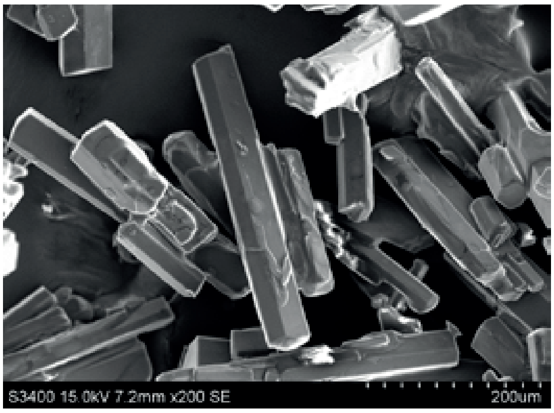


SUMMARY OF ACHIEVEMENTS

The CO_2 Capture Sub-Programme has achieved the following:

Solvent technology

- For the new class of precipitating absorbents, fully range vapour-liquid-solid equilibrium measurement has been carried out, and the region for crystal (figure below) formation and dissolution has been studied. A preliminary study of the integration of a precipitating CO_2 capture in an NGCC power plant in Task 1.6, has shown an 11% reduction in capture unit penalty compared to an MEA based capture unit. Oral presentation at PCCC3 covering Integration of precipitating capture in an NGCC power plant.



Crystallized sample SEM imaging.

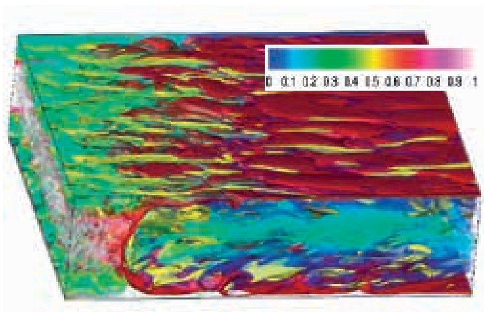
- PhD candidate Nina Enaasen Flø defended her PhD successfully on September 4, 2015.
- Dynamic model validation paper has been published in the International journal of Greenhouse Gas Control. The paper with time constants at the Tiller pilot is submitted to Computers and Chemical Engineering journal in May. Oral presentation at TCCS-8 covering the journal publication about dynamic model validation was held.

Innovative membrane technologies

- Up-scaled asymmetric tubular membranes for pre-combustion CO_2 capture and steam-methane-reforming applications are fabricated (figure below), and sealed with high-temperature glass-ceramic seal. First flux measurements of the tubular membrane up to 1000 °C are successfully perfomed.

Asymmetric tubular membranes.

- Peer-review dissemination: One paper accepted on Hydrogen Transport Mmembrane flux, one paper submitted on long-term flux testing, one oral presentation at international conference
- Studies on understanding the effect of nanoparticles in a polymer based membrane for post-combustion CO_2 separation continues in the KPN project HyMemCOPI.



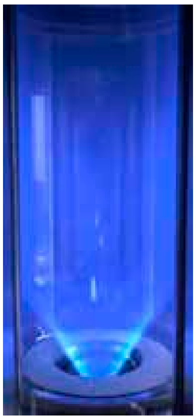
Flame (red surface) propagates in non-perfectly mixed reactants (colorscale) flowing in a duct.

Enabling H_2 fueled gas turbines

- A new Direct Numerical Simulations was completed in early 2015 (figure previous page), and data analysis has revealed important aspects of flashback occurring in a stratified (non-homogeneously mixed) reactants in hydrogen-fired gas turbines. Stratified combustion is a highly relevant condition to modern low NOx gas turbine combustors.
- Analysis of a second set of DNS datasets, representing injection of three IGCC-type syngas fuels with different degree of carbon capture (H_2-N_2 only, CO-lean H_2-N_2, CO-rich H_2-N_2), revealed that flame anchoring characteristics are nearly unaffected by the specific fuel composition as long as hydrogen is present in the fuel.

Oxy-fuel technologies

- Oxy-fuel combustion at a scale that is relevant for actual gas turbines has been studied using the HIPROX facility (figure to the right). The burner developed at SINTEF has been tested at thermal power loads up to 40 kW and 5 bar pressure. The potential for emissions of unburned CO is quantified as a function of parameters such as pressure, power, oxygen concentration and excess.

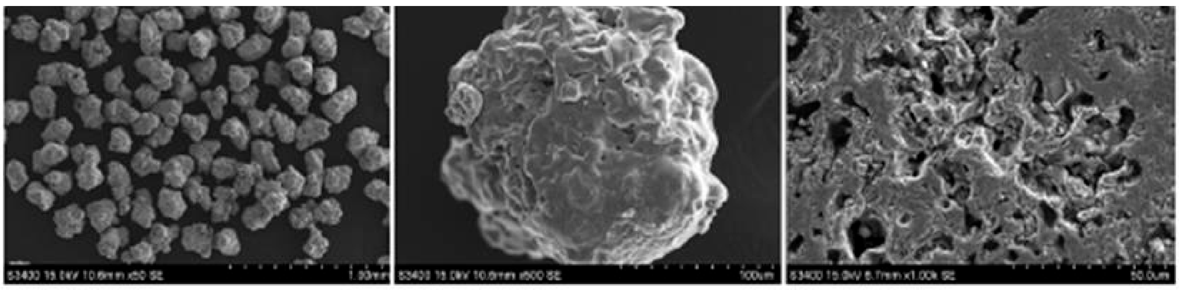


HIPROX facility

- In order to demonstrate a gas fired oxy-fuel cycle, DEMOXYT Infrastructure, the commercial 100 kW_e gas turbine has been delivered and commissioned in 2015, as part of RCN ECCSEL Phase 2 project.
- In the quest for lowering energy penalty in CCS concepts, the use of Exhaust Gas Recirculation (EGR) in pre-combustion power cycles are studied. The potential benefit of the technique has been published in terms of NOx emissions from the hydrogen fired gas turbine.
- The scientific output in 2015 has been four peer-reviewed publications in journals, 3 conference presentations, and the coordination of a workshop on "DNS for solid fuel flames".

Looping technologies

- The 150 kW CLC rig has been further modified and the heat-up of the entire reactor system to temperatures above 900°C (suitable for oxygen carrier particles, ilmenite) is successfully achieved.
- The PhD candidate has developed a numerical simulation tool for the fluid and particle flows in the 150 kW CLC reactor. The tool currently handles both reactors individually, considering chemical reactions in the reactors.
- New durable high capacity oxygen carrier materials, based on $CaMn(Ti)O_3$ system substituted with iron, have been developed. Three different batches of materials produced in amounts suitable for the 3 kW hot rig and by methods that is possible to scale up has been tested and evaluated (figure below).
- In continuation of the work on High Temperature CO_2 Sorbent, we have studied the effects of steam and how this influences the working capacity of CaO and calcined dolomite (MgO-



Scanning electron micrographs of CaMn(Ti)O3 subsituted with Fe. From left to right: overall view, focus on one granule, cross-section of a granule.

CaO) at different operating conditions. We have initiated a modelling activity to describe and analyze observed performance trends, and have applied in-situ X-ray diffraction and in-situ Infrared Spectroscopy.

- The Chemical Looping Combustion model was developed further to include hydrogen as fuel. The model was used to simulate industrial steam generation processes for refineries and benchmark against gas boilers.

Application to industry and offshore

- A model for CO_2 capture from refineries using MEA was established in HYSYS. The model was automated by developing a HYSYS Visual Basic tool to manipulate parameters, run case studies and export results to Excel. The effect of CO_2 capture rate on the specific reboiler duty was studied.
- Steam cycle design for an offshore oil and gas installation with CO_2 capture was performed keeping in mind the constraints of space and weight. Three different steam cycle configurations were designed, modelled, and simulated. In addition to the energy and mass balance results, a weight assessment of the major equipment was done.
- Collaboration with SP4 to include the attainable region approach for design of membrane processes.

Integrated assessment

- Review paper "Hydrogen production with CO_2 capture" submitted to International Journal of Hydrogen Energy. The paper provides an overview of technology option for H_2 production from fossil fuels with CO_2 capture.
- Sizing and costing has been undertaken for the Natural Gas Combined Cycle (NGCC) power plant with solvent capture for MEA and a Novel Generic Solvent (NGS), and also for the NGCC with Ca-looping capture.
- CO_2 capture for the NGCC with polymeric membranes (90% capture rate) was investigated for three different combustion configurations: conventional gas turbine, gas turbine with exhaust gas recirculation (EGR) and gas turbine with EGR + Supplementary Firing (SF). The NGCC + EGR option was found to have the best performance with a capture penalty of ~10%-points. However, the study clearly indicates that membrane capture from the NGCC has its optimum performance at lower capture rates (~60%).

HIGHLIGHT

From #SINTEF energy blog

Hydrogen cars: The role of fossil fuels and CCS in a cleaner transport system

Kristin Jordal, David Berstad and Petter Nekså

In short, a possible solution for hydrogen production for cars could be to use fossil fuels. We will tell you why and how!

Currently, road transport contribution to global CO_2 emissions is around 23%.

The main options to reducing the CO_2 emissions from the transport sector are electric cars and fuel cell cars powered by Hydrogen vs. electric cars.

Hydrogen vs. electric cars?

Norway has had a tremendous increase in electric cars on the roads over the past few years, and now the interest in fuel-cell cars is also increasing. We will not venture to predict what type of cars will be the winner in the long run in Norway or internationally – or whether we will have transport systems where both types have their roles. However, in order to significantly reduce the CO_2 emissions from the transport sector, the use of these types of cars should increase substantially.

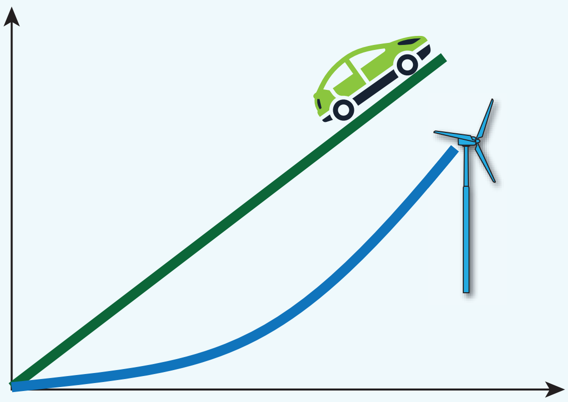
A substantial increase in the use of electric cars on a global scale will require a considerable increase in electric power generation capacity, whereas a substantial increase in fuel cell-driven cars will require a considerable increase in hydrogen production capacity.

We will not venture to predict what type of cars will be the winner in the long run in Norway or internationally

More energy only from renewable sources?

Ideally, in the long term, all the required power generation and/or hydrogen production for cars should come from renewable sources.

However, a rapid increase in the use of non-CO_2-emitting cars could be necessary to meet CO_2 emission reduction targets, an increase that is more rapid than what the increase in renewable energy can match. Also, fossil fuels are available, abundant and not unlikely to be employed both for electric power and for hydrogen production in many years to come.



A rapid increase of hydrogen and electric cars is necessary to meet CO_2 emission reduction targets, but is not matched by the increased production of renewable energy.

Hydrogen production relies on fossil fuel

Globally, current hydrogen production relies to more than 90% on fossil fuels. Consequently, for the transport sector to reduce its contribution to global warming, this use of fossil fuels would have to be combined with CCS (CO_2 capture and storage).

Hydrogen production, liquefaction and transport by ship to Japan was described earlier by David Berstad and Petter Nekså in Norwegian business daily "Dagens Nærlingsliv" and on gemini.no. This study found that the hydrogen rate relevant for export to Japan (225 kilo-tonnes per year as base case) cannot realistically be produced and liquefied based on renewable energy sources, as this would require 10–12 % of the current Norwegian electricity generation capacity as well as tremendous extension of power transmission capacity to the location of production. The most realistic solution would be to base hydrogen production on natural gas reforming with CCS, which would consume only roughly 1.5 % of the gas production volume. A gradual phasing-in of renewable energy should be considered if this capacity increases sufficiently.

An option: Norwegian natural gas with CCS to produce hydrogen

Hydrogen can be produced from electrolysers using electricity as well as from natural gas, in combination with CO_2 capture (CCS). Electrolysers have the advantage of being able to respond quickly to load changes from wind or solar power.

Hydrogen production from natural gas, on the other side, is a process with slow load response – but natural gas is available in large quantities in Norway: The energy contents of the gas exported from Norway annually is about ten times that of the annual Norwegian hydropower production.

Hydrogen for cars from coal with CCS?

From a global perspective, coal is a more abundant energy source than natural gas, and hydrogen production from coal, in combination with CCS, could also play a role when reducing the contribution to global warming from the transport sector. SINTEF researchers recently presented a concept for coal-based hydrogen production and liquefaction that shows how a self-sustained process with CO_2 capture could be designed (in addition to hydrogen, the process generates the power required for CO_2 capture and H_2 liquefaction). The concept is just as applicable for hydrogen production from natural gas.

The energy contents of the gas exported from Norway annually is about ten times that of the annual Norwegian hydropower production.

In short, a possible solution for hydrogen production for cars could be to use fossil fuels (natural gas or coal) with CCS for "base-load" hydrogen production, and gradually combine this with the use of electrolysers at times when electricity prices are low, due to abundant wind and solar power on the market. It remains to be determined through further research how the electrolysers and fossil fuel reforming can be combined in practice in the best possible way to generate close to emission free hydrogen for fuel cell vehicles. In such studies, also the role of electric cars could have a role.

INNOVATION AND INDUSTRY BENEFITS

Innovation	TRL*	Benefit / Impact
Precipitating system for post combustion CO_2 capture.	3-4	This technology will be of benefit to organizations that work towards reducing carbon footprint in the industries.
A novel distributed injection system for hydrogen-rich gaseous fuels	3	A novel fuel injection concept, especially aimed at gaseous hydrogen, is proposed for gas turbines applications. Traditional fuel injection takes place through transverse jets of the fuel issuing into the oxidant cross-flow, the new concept proposed in BIGCCS makes use of porous steel diffuser, complete of opportune coatings (ceramic/membrane), that achieve a better distribution of the fuel entering the combustor's premixer section and avoids point sources.
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.
H_2 production from natural gas by hydrogen transport membranes	3	Steam methane reforming with CO_2 capture using catalytic membrane reactors.
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.
A 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.
The 150 kW CLC test rig	3-4	This is a large test rig for CLC experiments. It is a product that can be used to validate new oxygen carriers and to develop new control strategies for CLC operation, all at close to industrial scale.

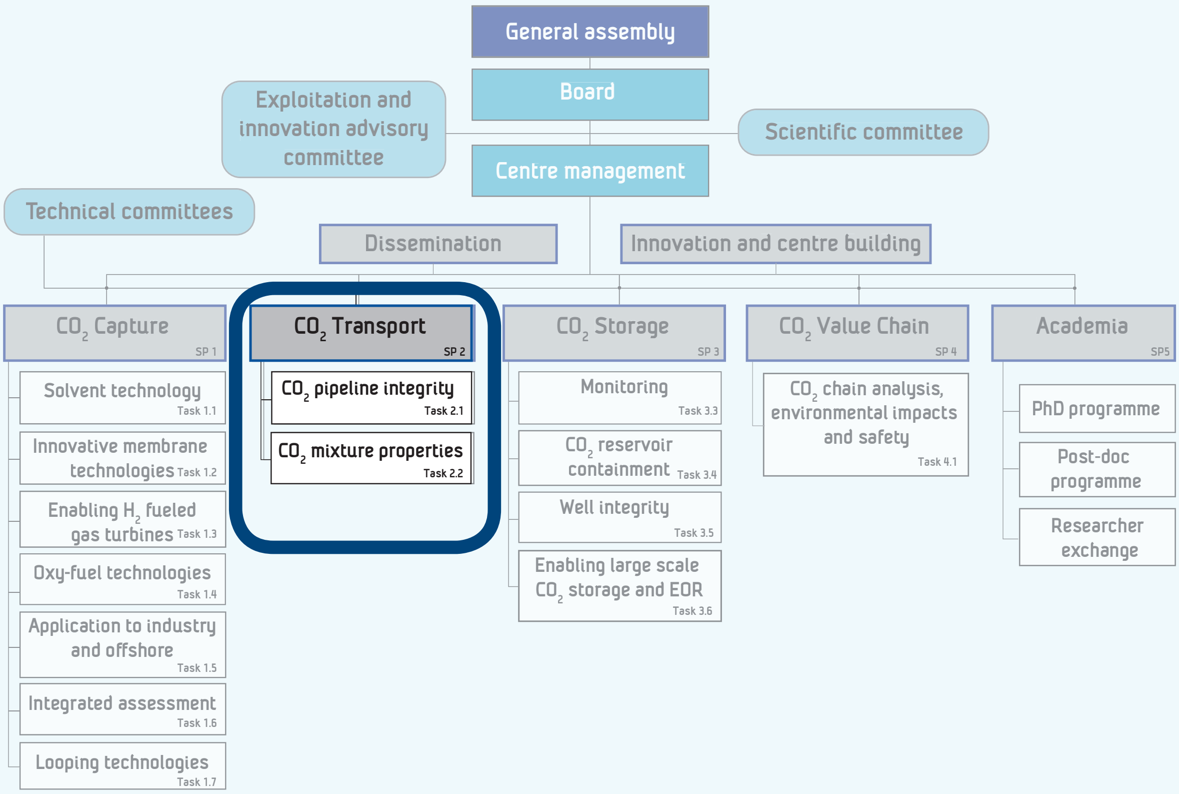
** Technology readiness level*


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.

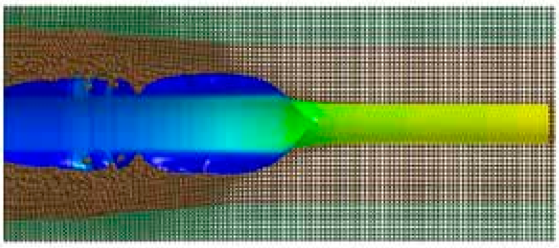


SUMMARY OF ACHIEVEMENTS

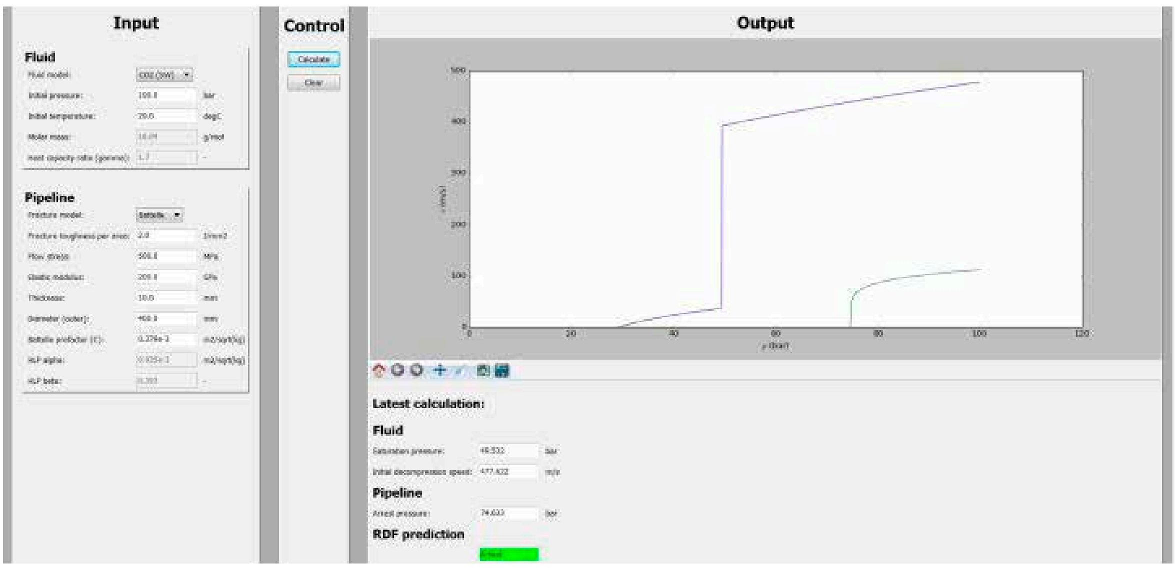
The work in the CO_2-Transport Sub-Programme is particularly relevant for safety, and therefore also economy. The CO_2 property data being acquired are necessary to perform accurate calculations. The first application will be transport, but accurate models for thermophysical properties will become more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

We succeeded in validating the model against two full-scale experiments conducted by SINTEF in the CO2PIPETRANS project – led by DNV-GL

- A coupled fluid-structure model which can calculate running-ductile fracture in transport pipelines is developed, and which therefore can contribute to safe and economical CO_2-transport. We succeeded in validating the model against two full-scale experiments conducted by SINTEF in the CO_2PIPETRANS project – led by DNV-GL. This was an important milestone in our work, and represents an important step in promoting the model and our method for further use in design and operation of CO_2 pipelines (see figure below). There is today no other existing model framework that approaches both the fluid and material aspects of the problem through physics-based arguments and equations as we do – let alone also including the complex thermodynamics of dense-phase CO_2.



Coupled fluid-structure simulation of running-ductile fracture (RDF). The CO_2 is invisible, but the pressure exerted on the pipe is colour-coded. The pipe is half buried and the "beads" represent soil elements.



BIGCCS graphical user interface (GUI) for engineering methods for fracture propagation control.

- An important difference discovered in the resulting crack-driving forces between natural gas and CO_2 in a running ductile fracture in a pipeline was discovered: CO_2 gives a larger pressure over a longer distance than natural gas. This is one important reason why the existing framework is not applicable to CO_2-rich fluids.
- We have developed GUI for a semi-empirical method in use in industry today (see figure on bottom of previous page). Although we do not recommend this method for CO_2 pipes (see above), the Graphical user interface is useful for illustration purposes. Furthermore, our future goal is to develop an engineering method based on insights from our full physics-based model and available experiments.
- An equilibrium cell is developed for gas-liquid equilibrium of CO_2-rich mixtures at pressures and temperatures relevant for CCS. During the year, thorough measurements of world leading quality have been performed on CO_2-O_2 and CO_2-Ar in the SINTEF-NTNU lab. As seen in the figure below, the previous literature data are scarce and scattered, which is reflected in a poor model situation. In fact, for four out of the six isotherms, the deviations between the best existing model and our data were more than 10 bar in the critical region. Such a large pressure difference could have a large cost impact in the design of different processes.

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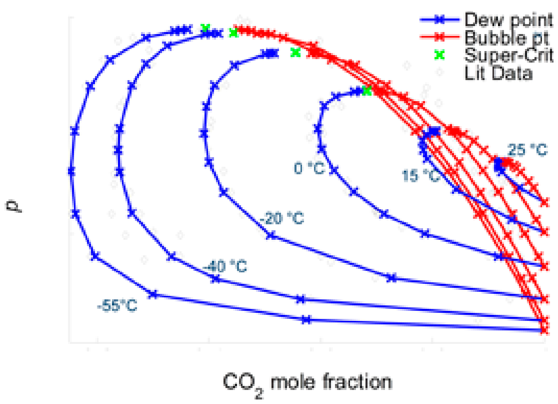


BIGCCS/CO_2Mix CO_2-O_2 vapour-liquid equilibrium measurements.

- For CO_2-Ar, the formation of a solid phase was also studied. The knowledge gained is of value both for the optimization of low-temperature processes and to understand sudden depressurizations.
- New binary interaction parameters (for property models) based on the vapour-liquid equilibrium measurements have been produced and distributed to the industrial partners of BIGCCS.
- At RUB, density has been measured on the CO_2-Ar system.
- A two-day seminar was arranged for BIGCCS partners (see highlight), and a SP2 side-event was arranged during the BIGCCS Consortium day.
- Seven presentations from BIGCCS SP2 have been given at international conferences and workshops.
- New contacts have been established with MIT and University of Western Australia. The existing contact with NIST has been extended.
- A CSLF report on technical barriers and R&D opportunities for offshore, sub-seabed geologic storage of CO_2 was co-authored.

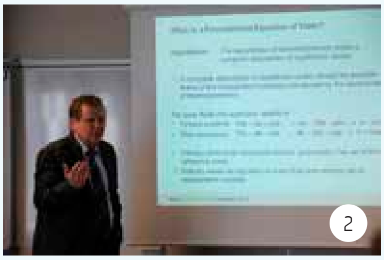
Dr Jacob Stang working on the vapour-liquid equilibrium setup. Photo: SINTEF/Sigurd W. Løvseth.

HIGHLIGHT

Models, data and software for safe and efficient CO_2 transport

A two-day technical meeting and seminar in the BIGCCS CO_2-transport programme took place May 27–28, 2015 in Trondheim. The first day was dedicated to technical presentations, emphasizing the activity in the task on CO_2 mixture properties (a.k.a. the CO_2Mix project), which concluded at the end of 2015. On the second day, the industry participants could try CO_2-transport software on their own computers. The goal to design and operate CO_2-transport (and CCS) systems safely and efficiently requires quantification. In this respect, the BIGCCS CO_2-transport programme has two main contributions:

- A unique coupled fluid-structure model has been developed for fracture-propagation control in CO_2-transport pipelines. With some further validation and development, it may reduce the need to perform full-scale tests to design CO_2-transport pipelines safe against running-ductile fracture – where today's engineering methods fail.
- Unique and accurate thermodynamic data are being generated. They will be employed to improve thermodynamic property models, which, as of today, are not always accurate for CCS applications. In particular, the vapour-liquid equilibrium cell developed in the CO_2Mix project, may be the world's most accurate.



1: Dr Morten Hammer (SINTEF Energy Research, centre-right) showed the seminar participants how to change interaction parameters in a commercially available thermodynamic software package.
2: Professor Roland Span (RUB) demonstrated the TREND thermodynamic-property library and gave an introduction to the basics.
3: Dr Håkon Nordhagen (SINTEF Materials and chemistry) showed the details of the BIGCCS coupled fluid-structure model for fracture-propagation control in CO_2 pipelines.
All photos: SINTEF/Svend T. Munkejord.

The details of the seminar are available to consortium members in the e-room. Further, researchers from the BIGCCS CO_2-transport programme gave four presentations on the topic at the eighth Trondheim CCS Conference, TCCS-8.

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.

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.

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.

Result	TRL*	Impact
Numerical tool for fracture propagation control in pipelines	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	4-6	Preparation of gases with an accuracy in composition of the order of 1 ppm in a 10 litre gas cylinder. It can be used for a range of fluids and quantities
CO_2Mix Phase equilibria setup	4	1. Construction and improvement of thermophysical property models for CCS-relevant fluids and conditions.
Redesign for CCS fluids and conditions of setup for measurement of density and speed of sound	4	2. Design of similar setups for other fluids or conditions. 3. Results are needed for realization of CCS systems at all TRLs

** Technology readiness level*

ACADEMIC ACHIEVEMENTS

- We were invited to write a review paper on CCS and CO_2 transport for the *Applied Energy* journal. The paper will be published in 2016.
- Two articles were published in peer-reviewed international journals, and more are expected in 2016. So far, SP2 has published 21 peer-reviewed articles and two popular-science articles.
- Two PhD theses were written on the subject of thermophysical properties, and they will be defended in 2016. Snorre Foss Westman (NTNU) studied gas-liquid equilibria of CO_2-rich mixtures, while Robin Wegge (RUB) studied the density and speed of sound.
- One master candidate, Aleksander Reinertsen, was supervised in SP2, on the subject of *models and numerical methods for two-phase flow of CO_2 in pipes.*

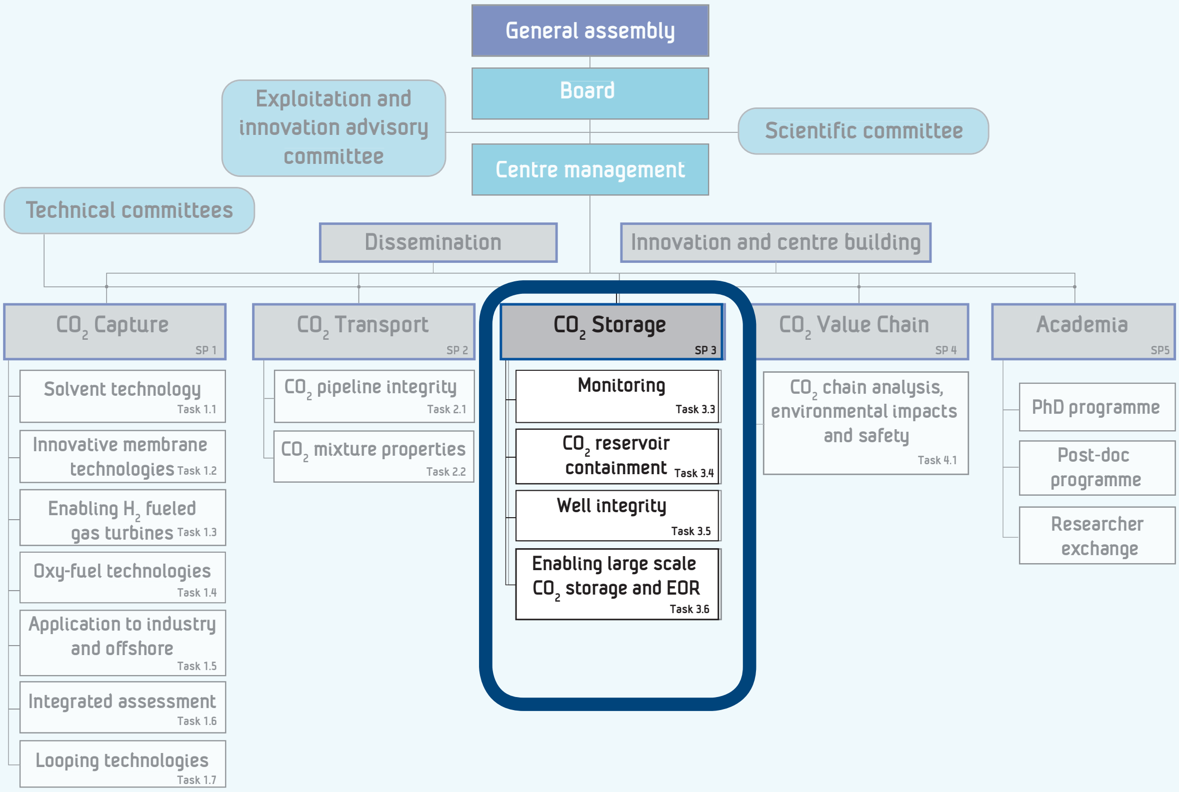

CO2

Grethe Tangen

CO_2 storage (SP3)

CO_2 storage builds on the same properties that have kept oil and gas underground for millions of years. Safe and efficient storage of CO_2 is industrially demonstrated and is already technically viable at large scale. Nevertheless, we are still awaiting the market pull that can accelerate the deployment of CCS.

The outcomes from the 2015 UN Climate Conference (COP21) confirm that we should keep up the momentum of our struggle for low carbon energy solutions and thus continue the technology push. The research conducted in BIGCCS SP3 aims at strengthening the business case of CCS by developing knowledge and technology for optimal storage of CO_2 at a lowest possible cost, including documentation of the permanent containment of CO_2.



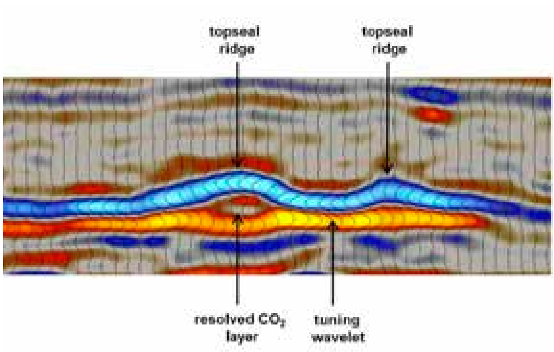
SUMMARY OF ACHIEVEMENTS

CO_2 Monitoring
(including the KPN project uniCQue)

The main objective of the Monitoring task is to improve CO_2 storage safety by accurately localizing the CO_2 plume, quantifying CO_2 volumes, and enabling early detection of potential leakage. In 2015, specific highlights include:

- Significant improvements of **high-resolution images of CO_2 plume at Utsira with clearly visible thin layers** using Full Waveform Inversion and a recently developed migration code (LS-RTM).
- Development and first tests of a Python (programming language) **work bench for geophysical inversion methods** (Full Waveform Inversion and Controlled-Source Electro-Magnetic inversion) **with uncertainty quantification.**
- Development of **method for volumetric estimation of subsurface fluid substitution** based on the analysis of 4D seismic time shifts.

... revealing detailed insights into layer properties and variability, to a precision not previously achieved.



Section through topmost layer showing explicit resolution (separation) of top and and base layer reflections (blue and orange respectively) beneath two ridges (BGS).

- **Forensic analysis of a carbon-dioxide layer at Sleipner** from time-lapse 3D seismics revealing detailed insights into layer properties and variability, to a **precision not previously achieved.**

Espen Birger Raknes successfully defended his PhD thesis titled "Three-Dimensional Elastic Full Waveform Inversion". A summary of the thesis is found at the BIGCCS Web.

From left: Martin Landrø (NTNU), Frank Maaø (Statoil), Espen Birger Raknes (NTNU), Stewart Greenhalgh (ETH Zurich), Børge Arntsen (NTNU).

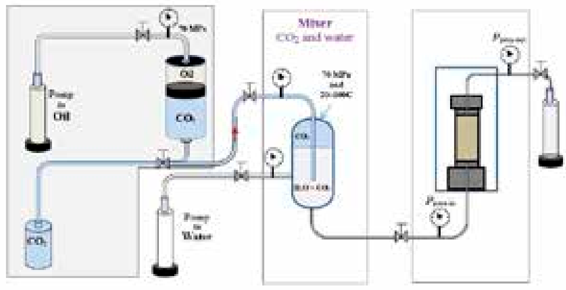
A new post-doc Manuel Amaya-Benitez started November 2015 in the KPN project (uniCQue). He will work on improving the uncertainty quantification techniques while keeping them computationally feasible.

CO_2 reservoir containment

For the period 2015-2016, the objective of this task will be to help maximise injected volumes in planned storage sites by **lowering the uncertainty in prediction of potential ill-effects such as leakage due to fracturing.** In particular, attention will be given to injection into mature fields where irreversible straining may have already occurred. Highlights from the research during 2015 are:

- **Composite cement-rock plug mechanical testing** show surprising interface strength for drained sandstone conditions at relevant downhole stress conditions – *peer-reviewed paper presented at ARMA 2015, technical note to be published in peer-reviewed journal.*
- Fatigue tests run on weak sandstone analysed for **permanent strain accumulation in depleted reservoirs** reveal surprisingly that strain occurs in opposite direction to that expected – *paper presented at TCCS-8, submitted to Energy Procedia.*
- Combined geochemical and geomechanical analysis of exposure tests on two sandstone plugs reveals **negligible strength loss**, even though mineralogy shows significant changes, also seen as permeability loss in one plug – *paper presented at TCCS-8, accepted for publication at Energy Procedia.*
- Continued work on **fault reactivation tests inducing slip** (BGS) has provided interesting results, showing that fault reactivation only occurred once using CO_2. The activity has resulted in several presentations and publications during 2015.
- Work related to **laboratory testing of shale plugs with respect to creep and crack healing potential** is progressing, and will continue early 2016.

New post-doc Nicolaine Agofack started summer of 2015. He will work in the laboratory with investigations of CO_2 partial saturation effect on seismic frequency velocities. The goal will be to assist monitoring efforts in detecting small quantities of CO_2, so as to increase seismic resolution of plume spread in the underground and early warning in case of leakage. Initial efforts are dedicated to plan a laboratory set-up whereby rock plugs can be repeatedly saturated with the desired CO_2 saturation, for as broad a range as feasible. The method chosen is injection of CO_2-saturated brine into the plug, kept at given stress and pore pressure conditions. The pore pressure will then be carefully lowered to allow for CO_2 to come out of solution, in gaseous phase. Velocities will then be measured for as many different partial saturation conditions as possible.



Experimental set-up for partial saturation effect on velocities.

PhD student Dawid Sczewczyk: Effect of shale saturation on the seismic attributes - Runner-up to best presentation at international workshop in Perth, Australia. Dawid has published a summary of his work on the BIGCCS web page.

PhD student Sohrab Gheibi: Numerical simulations of a Brazilian test - Peer-reviewed paper at ARMA 2015. Sohrab also presented his work at the Climit PhD seminar in September: Stress Path Evolution Associated With CO_2 Storage Reservoirs.

In January 2015, the integrated KPN project *Fundamental effects of CO_2 on rock properties* (FECRP) was concluded with very good feed-back from the Research Council.

The main results from the completed FECRP KPN

- Loss of injectivity due to thermal stress and fracture initiation – numerical analysis high-lights conditions for caprock shale fracturing.
- Laboratory investigation of thermal stress development in shale specimens suggests a lower risk of fracturing than stipulated by the simulations.
- Rock fatigue and fracturing due to intermittent injection and shut-in – laboratory experiments were conducted on hollow cylinder sandstone specimens, suggesting no fatigue likely to occur.
- Cyclic loading of an idealized clay-filled discontinuity and the role of mineralogy on flow and fracturing due to intermittent

injection and shut-in – a unique laboratory set-up was built at BGS.

- Caprock properties and the effect of intra-formational sealing layers – internal structure of high permeability storage sites comprising low permeability thin structures can lead to both incomplete CO_2 filling as well as incomplete imbibition during the equilibration stage.
- Rock Wettability Alterations due to Exposure and Aging in Aqueous CO_2 Environment – an efficient routine to investigate wettability changes upon CO_2 exposure was implemented by the post docs in the KPN.
- Determination of CO_2 capillary entry pressure as function of wettability alterations – an apparatus was set up by which the capillary entry pressure into a shale caprock could be measured.

A popular science article published at the Climit web site (in Norwegian) summarise the results from the project: *www.climit.no.*

CO_2 Well Integrity

(including the KPN project CO_2 Well Integrity and the researcher projects CO_2 Plug)

The overall objective of this task is to improve CO_2 storage safety and cost-efficiency by obtaining a more detailed understanding of *how*, *when*, *why* and *where* leaks develop in CO_2 wells. This can hopefully lead to improved prediction, prevention and remediation of well failure in the future.

This can hopefully lead to improved prediction, prevention and remediation of well failure in the future.

The work was started in 2014, and has focused on mapping how cement bonds to steel and rock during well construction. This involves studying the influence of various downhole fluids, rocks and filter cakes. Leakage paths have been described in detail, and we have also developed a model to estimate leakage rates through them. During the first quarter of 2015 we also developed a new code that can be used to study the placement of cement (or other sealants) in wells.

The main focus in 2015 has, however, been on understanding more about how well integrity can be lost *after* well construction as a result of CO_2 exposure or downhole temperature variations. Experiments done, together with our partner GEUS from Denmark, involved core flooding of samples using supercritical CO_2. This work has demonstrated that CO_2 flow can actually close cracks present in well cement through the precipitation of $CaCO_3$. **This is good news for CO_2 storage safety, as it suggests that CO_2 leakage along cracks in cement is self-limiting – and that CO_2 could be a useful well remediation fluid.** The drawback is, however, that the presence of drilling mud on leakage path surfaces seems to inhibit the beneficial self-healing effect. Ongoing work, together with Lawrence Livermore National Laboratory, focuses on understanding this process in more detail.

Temperature variations in wells can cause loss of cement integrity, and this is also studied in Task 3.5. We have discovered that material selection (e.g. the replacement of cement with a thermally insulating/conducting material) significantly affects downhole thermal gradients. It has also been found that defects in the cement (cracks or voids) reduce a well's resistance towards temperature variations. Even if the defects are not initially connected, they are found to act as nucleation sites for further cracking/debonding – which can ultimately lead to long connected leakage channels for CO_2. **These findings underline the importance of achieving a good primary cementing job in wells that will be used for CO_2 injection.**

Sandstone-cement sample before (left) and after (right) exposure to CO_2 through a water-alternating-gas (WAG) flooding scheme. As seen in the raw micro computed tomography images in the middle of the figure, the three-bladed crack in the middle of the sample has closed up after exposure. This is also easy to see in the 3D reconstruction in the bottom of the image.

A new PostDoc started in May 2015. Her name is Elvira Chavez, and she works in the researcher project CO_2plug. Elvira focuses on X-ray tomography studies of cement and other well plugging materials. She has already visited several European laboratories and synchrotron facilities to make use of state-of-the-art research tools in her experiments.

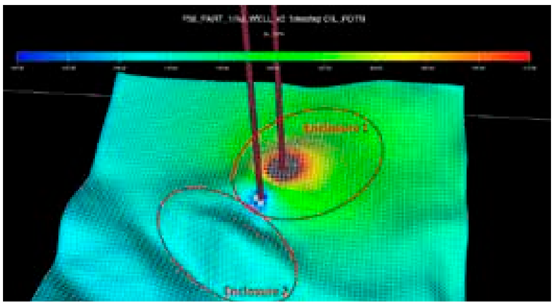
Enabling large scale CO_2 storage and CO_2 EOR

The overall objective is to contribute to closing knowledge gaps preventing development of large-scale CO_2 storage. The focus is on issues related to **pore pressure increase when CO_2 is injected at rates in the Mt/year range**. In addition, this task cooperates with SP4 on the development of updated CO_2 EOR modules for the BIGCCS value chain model.

In 2015 work on pressure management are developed along two main directions, both extending work in BIGCCS from 2014 and earlier.

Geomechanical data from wells in the Bunter sandstone region have been re-analysed to match observations with lithologies. This is done to **produce better data to test the hypothesis that the stress regime in the strata overlying the thick salt deposits is detached from the prevailing stress patterns in the basement rocks.** The stress regime is important for the work to better constrain pore pressure limits for fracturation and fault reactivation, and thus for a more accurate determination of achievable CO_2 storage capacity.

Modelling and simulation work is **continued to investigate how CO_2 injection and formation water extraction wells should be operated to maximize storage capacity and minimize operating costs** when two storage sites are operated nearby in the same formation. The pore pressure disturbance (increase) from a CO_2 injection operation will travel much farther than the CO_2 plume itself, and will cause storage capacity in nearby traps to be reduced unless the pressure is managed, e.g., by extraction of formation water. Placing the extraction wells between the two injection sites seems to be the most efficient use of the additional investment, and the total water extraction rate should be of the same order of magnitude as the CO_2 injection. Detailed optimization depends on whether the extraction wells are active (with pumps) or passive, and on other cost parameters.



Example with a single water extraction wells "protecting" the future injection site in Enclosure 2.

HIGHLIGHT

From gemini.no

How are we going to store the problem gas CO_2?

CO_2 is the great scapegoat of our age. Is there a way to get rid of it by burying it in the ground or beneath the sea bed?

By Åse Dragland

"If we want to inject gas underground or beneath the sea bed, we will have to monitor what happens to it. We have to be entirely sure that it stays where it's supposed to". So says SINTEF researcher Peder Eliasson. He and his colleagues in their office building opposite Lerkendal Stadium, are analysing seismic and electromagnetic data taken from the CO_2 sequestration reservoir below the sea bed at the Sleipner field in the North Sea.

"But how can we be sure that the gas will stay where it's supposed to"?
"By interpreting geophysical data. During seismic surveys, we send down acoustic signals that are then reflected back, enabling us to determine distances and dimensions on the basis of the echoes. We then use these to determine the location and extent of the gas. What we do is compare the seismic data before and after injection", says Eliasson.

He says that there are many centres around the world studying data from various CO_2 storage reservoirs, because it is important to learn how to make the best possible use of this information. He maintains that certainty is the key factor in CO_2 sequestration. The risk of leaks is very small, but this has to documented very accurately. Measurement equipment must be robust and not too expensive, and the data must be accurate. It must also be possible to customise the analyses.

CO_2 has become the symbol of human consumption and industrial production. The gas that pours out of cement factory chimneys and belches out of exhaust pipes and combustion plants is the reason behind the biggest environmental challenge of our age.

Climate change challenge

CO_2 has become the symbol of human consumption and industrial production. The gas that pours out of cement factory chimneys and belches out of exhaust pipes and combustion plants is the reason behind the biggest environmental challenge of our age. This is why researchers all over the world are working to find sound ways of capturing CO_2 and pumping it beneath the surface of the earth, where it can remain safely stored away for thousands of years.

Numerous industrial projects have demonstrated that this is possible. However, there is a great deal of work still to be done before an optimal CO_2 storage solution is in place. The question is also whether we can store volumes large enough to help prevent global temperatures increasing by more than two degrees.

Norway leading the way

At the Sleipner gas field, Statoil operates the oldest CO_2 sequestration project in the world, with around 15 million tonnes of CO_2 already stored underground – more than the amount generated by all the cars in Norway in a two-year period. Almost one million tonnes are pumped down beneath the sea bed every year.

In 2008, CO_2 storage operations started from the processing facility on Melkøya in northern Norway. From here, gas is transported in a pipeline out to the Snøhvit field, where it is injected into a dedicated formation beneath the field's gas-bearing reservoirs. Eliasson says that SINTEF has been working for many years with the Norwegian University of Science and Technology (NTNU) and the UK-based company BGS on the development of methods to make monitoring more accurate and reliable. Over the last few years, it has also been working with GFZ in Germany, where researchers have established a land-based pilot for the injection of CO_2 to a depth of 600 metres underground. Since 2014, Norwegian researchers have been in contact with the University of Illinois about the Decatur project in the USA, and with CaMI at its Field Research Station in Canada. But in general, testing has been on a small scale.

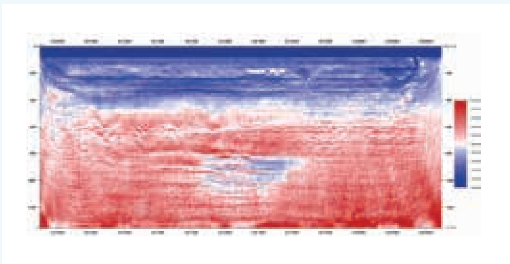
"SINTEF Petroleum Research is performing a range of experiments as a means of analysing CO_2 sequestration issues", says Eliasson. "We are researching into everything from how the gas behaves in the reservoir and how great the risk is for leaks through the caprock or wells, to calculations of storage capacity and the development of monitoring methods. The latter is my speciality. Elsewhere at SINTEF, research is focusing on the major BIGCCS research centre", he says.

Monitoring could be better

A CO_2 sequestration reservoir beneath the sea bed must be at least 800 metres below the sea surface if it is to exert a pressure that gives the gas a density similar to that of water. This makes storage more efficient. Seismic images from the Utsira Formation at the Sleipner field indicate that the reservoir is stable and is not leaking gas up to the sea bed.

Eliasson digs out a chart. It shows the gas as a thin, blue layer surrounded by a red area. Over the last few years, the gas at Sleipner has migrated to the top of the sandstone layer, and is lying in a thin band beneath the impermeable shale that forms the roof of the reservoir.

"The field is blue. Why is that"?
"Variations in seismic velocity are represented by different colours. In areas where CO_2 is present, sound waves travel more slowly than in the surrounding rocks. This is expressed by the blue colour in the figure. However, it's not enough for us merely to obtain an image of the gas that is down there. According to Eliasson, the images don't tell us anything about what degree of certainty we have, or whether there is a risk of small leaks. He believes it is essential for us to find out how much is there, and to put a figure on our margin of uncertainty. Is it ten million tonnes plus/minus 50 per cent, or is it plus/minus 5 per cent?



Seismic model that shows thin layers of CO_2 at the Sleipner field in 2008. The variations of the sound are represented by different colours. Red is high speed, blue is low.

We need to achieve the highest possible degree of certainty, and that is why researchers are studying several different types of data. “We’re looking at multiple data sets, and combining seismic data with electromagnetic and gravimetric data in order to achieve the best possible result”, says Eliasson.

A question of money

One obstacle in the way of large-scale CO_2 sequestration is the financial aspect. Modifying a coal or gas power station to capture its CO_2 involves a considerable increase in costs. On top of this, it would be necessary to build the infrastructure to transport the gas to its final storage location.

The costs of capture and storage are significant.

“Even though the licence-holders at Sleipner Vest would have to pay a huge amount per day to the Norwegian government if the gas did escape into the atmosphere, as long as international CO_2 emissions don’t cost any more than that, it isn’t profitable for the industry to invest more in capture and storage”, says Eliasson. “One scenario is to create a global system of duties related to CO_2 emissions, and for governments to play their part and develop the necessary infrastructure. That would open up a range of new opportunities”, he says.

Storage is essential

Most political signals suggest that fossil fuels will dominate global energy supply until the middle of this century. The IPCC also says that CO_2 sequestration is essential if we are to achieve emissions reductions that really make a difference.

In Brussels, carbon capture is attracting new attention, and many public and private sector players are realising that there is an urgent need to get the technology in place. The EU Commission is now trying to get better subsidy schemes in place from 2020. The most emission-intensive areas of northern Europe have no real alternatives to CO_2 capture and storage. This means that there will be a huge demand for a sequestration infrastructure.

It has been pointed out that this type of storage could be a practical tool that will allow humans to carry on burning fossil fuels.

Sirin Engen admits on Bellona’s website that this is a technology that would allow the oil and gas industry to play a role in the transition to a low-emissions society. “But this is not a rescue mission, and it does not absolve the industry of its responsibility to cut CO_2 emissions”, she says. Peder Eliasson at SINTEF does not want to make predictions or express an opinion on the moral aspects here. “Our task is to be objective and to contribute with new knowledge and technologies”, he says. However, like many others, he believes that CO_2 capture and storage could be one of the key factors driving the so-called ‘green shift’, where the petroleum industry will also play a part.

CO_2- storage in the world.

INNOVATION AND INDUSTRY BENEFITS

Innovation	TRL*	Impact
An automated CO_2 leakage detection tool (BGS)	4	A methodology to determine the detectability of small amounts of leaking CO_2 has been developed for time-lapse seismic data. The addition of synthetic leaks to seismic difference data allows the determination of leakage thresholds.
High-resolution CO_2 monitoring using acoustic and elastic Full Waveform Inversion (SINTEF/NTNU)	4	The method offers valuable input for more reliable quantification of fluid properties, pore pressure and saturation. It is based on a modelling engine simulating the propagation of seismic waves and an inversion engine seeking to minimize the misfit between observed and simulated seismic data (amplitude and phase) by iteratively updating subsurface properties.
CO_2 pressure and saturation discrimination using time-lapse seismic data (BGS)	4	A technique based on spectral decomposition methodology to determine the temporal thickness of CO_2 layers. Used to discriminate between direct fluid substitution and pressure changes in Tubåen and to verify that changes in the Stø reservoir primarily relate to fluid substitution effects, without a significant pressure increase.
Quantification of uncertainty in geophysical monitoring methods (SINTEF)	3	Approach based on Bayesian inversion (with prior data and model covariance) for imaging/monitoring methods. Methodology equally useful for applications ranging from exploration to monitoring of CO_2 storage and EOR.
Sealing efficiency of caprock shales (NTNU, SINTEF)	6	New laboratory methodology for testing of wettability changes and capillary entry pressure. An experimental core flooding rig for determination of capillary entry pressure dependence on caprock wettability change was also built. The innovation will help to ensure meaningful simulations needed to qualify trapping efficiency of formations above chosen storage reservoirs
Mechanical properties of cement to rock interface (SINTEF)	7	New laboratory methodology for routine testing of cement bonding using composite plugs. The innovation will help to ensure meaningful simulations needed to qualify well cements for lifetime performance
Thermal tensile stress test with IR lamps (SINTEF)	5	New laboratory methodology for routine testing of caprock samples for thermal stress risk. The innovation will help to quantify the different leakage risks from the outset of operations.
Fluid saturation dependent seismic dispersion in Mancos Shale (NTNU, SINTEF)	7	New biaxial compaction cell allowing for static, quasi-static and ultrasonic measurements on partially saturated samples. The set-up allows for controlled, partial saturation of CO_2 in sandstone specimens. Technology is a step forward in understanding monitoring data so needed during for example CO_2 storage where general public is concerned with possible leakages to the overburden.
Simulation tool for studying cement placement in wells (SINTEF)	4	A tool has been developed for simulating cement placement in wells. It captures important characteristics of cement slurry behaviour reported from the field. The effect of several factors can be studied by the new tool: (i) properties of cement and displaced mud/spacer, (ii) degree of casing centralization, (iii) borehole geometry/roughness. The tool can be used to optimize cement slurries to max-imize sealing in future wells, or to evaluate cement job success in existing wells. This is important in order to ensure leak-free CO_2 storage.
The use of CO_2 for healing cracks in cement (GEUS, SINTEF)	3-4	It has been investigated how CO_2 can be used for efficiently sealing cracks, pores and defects in cement. This has the potential to minimize leakage along wells penetrating CO_2 storage reservoirs, and it might also be possible to use CO_2 as a general remediation fluid in other wells (e.g. oil/gas wells or geothermal wells).
X-ray tomography studies of cements for safe plugging of CO_2 wells (NTNU, SINTEF)	3-4	The first X-ray synchrotron studies of well cement hardening have been made. These have resulted in a series of tomograms of high resolution that give insight into how and why leak paths are created during cement solidification through processes such as shrinkage and de-bonding. This is essential for optimizing cement slurries for long-term sealing in CO_2 wells.

Experimentally verified method for leakage prediction in CO_2 wells (SINTEF)	3-4	Knowing potential CO2 leakage rates along wells is important for assessing CCS-related risks. This new method can be used to obtain CO2 leakage rates in various well scenarios, and it can also be used to simulate the penetration of other fluids into leakage paths in/along wells (e.g. to optimize remediation of defects in wells).
Method for determining safe temperature intervals for CO_2 wells (SINTEF, LLNL)	2-3	A methodology combining experiments and modelling has been developed to study how, why, where and when well integrity is lost when a CO_2 injection well is exposed to repeated temperature variations. It can be used to determine safe temperature intervals for a given well, to optimize injection parameters to ensure long-term well integrity and to evaluate alternative well construction materials.
Operating pressure management in large scale CCS (GEUS, SINTEF, BGS)	3-4	Dynamic modelling for pressure management from water production (well configuration), can be used to mitigate unwanted operational influence between neighbouring subsurface activities to maintain injectivity and optimize storage capacity.
Analysis of Safe Injection Pressures (BGS)	5	Use of pre-existing borehole data such as breakout data and leak-off data to map regional stress field in storage formation and cap rock and thereby improve estimates of thresholds for safe injection pressure. This may allow less conservative operational constraints and increase utilization of storage formations.
Implementation of water production on Bunter (SINTEF)	2-3	Inclusion of artificial lift methods to be incorporated in the existing Eclipse simulation model, useful for quantifying the effectiveness of the various water production methods in terms of increased storage capacity or protected storage capacity in the case of a neighbouring license and if relevant cost data can be found, the alternative production methods can be compared in terms of cost per unit increased/protected storage capacity.

** Technology readiness level*

***Representatives of the BIGCCS CO_2 Storage Dream Team:** Peter Frykman (GEUS), Carsten Nielsen (GEUS), Nicolaine Agofack (NTNU), Dawid Szewczyk (NTNU), Sohrab Gheibi (NTNU), Jelena Todorovic (SINTEF), Kamila Gawel (SINTEF), Elvira Chavez (NTNU), Jim White (BGS), Peder Eliasson (SINTEF), Rob Cuss (BGS), Andy Chadwick (BGS), Alv-Arne Grimstad (SINTEF), Claus Kjøller (GEUS), Halvor Lund (SINTEF), Malin Torsæter (SINTEF), Pierre Cerasi (SINTEF).*

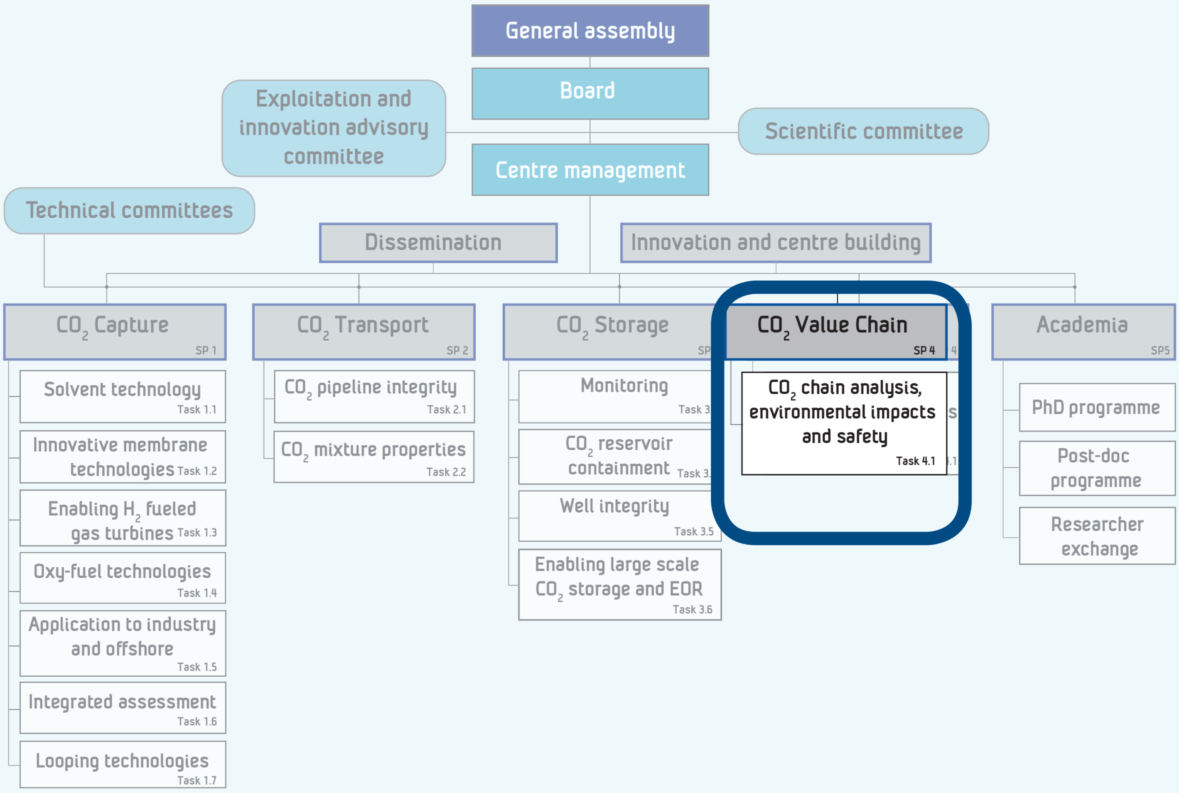
ACADEMIC ACHIEVEMENTS

SP3 aims to have a close collaboration with the PhD students. The students are invited to SP3 workshops and to a large extent they have participated. In addition to the students already mentioned in this report, **Amir Taheri, NTNU**, has successfully defended his PhDs theses in 2015: **Experimental and Numerical Study of Density-Driven Natural Convection Mechanism during Storage of CO_2 in brine aquifers.**

The title of the public lecture was "How induced fracturing may affect fluid flow during injection".

An article presenting parts of Amir's work was published on the BIGCCS Web page in May 2015. The article includes links to Youtube movies showing experiments about density-driven natural convection mechanism in Hele-Shaw cell geometries using CO_2 gas phase and brine.

***Final Ph.D exam for Amir Taheri June 24, 2015**. Jan Åge Stensen, Jon Kleppe, Ole Torsæter, Safoura Taheri, Amir Taheri, Dag Wessel-Berg, Arne Skauge, Andy Chadwick.*



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
Monitoring
CO_2 reservoir containment
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)

The CCS technology is available and could be applied in power generation sector as well as in industry. However, the investors and other stakeholders require confidence in income of acceptable size and duration over sufficiently long time period in order to initiate realization of a CCS project.

In order to stimulate decisions about initiation and commercial realization of CCS projects, the viability of CO_2 chains must be explored, including technological, economic, environmental, and organizational aspects. The many associated uncertainties must be explored, potential risks must be identified and measures for de-risking addressed.

A consistent and transparent methodology that allows critical evaluation of a CCS project with respect to multiple criteria was developed and a simulation tool for quantification of the Key Performance Indicators (KPIs) of an integrated CO_2 chain was implemented within SP4.

SUMMARY OF ACHIEVEMENTS

Specific achievements from the SP4 CO_2 Value Chain in 2015:

- We finalized the development of a new module for membrane-based CO_2 capture which can optimize and assess the design of membrane-based processes for post-combustion CO_2 capture.
- This new module was used to identify the membrane properties required for membrane processes to be cost-competitive with MEA based post-combustion CO_2 capture from a coal power plant. The impact of different uncertainties such as maturity and membrane cost was also investigated while the results were also put in the context of membrane development. Several partners have expressed very positive feedbacks on this activity.
- We have has investigated the cost of different chain design alternatives and scenarios for CCS from the Norcem Brevik cement plant and used this to identify and discuss some of the key barriers to the realization of CCS from the Norcem plant.
- The work has also contributed to establishing cooperation with other internationally leading groups. A budget extension of the PilotCCS value chain project with Czech Technical University (CVUT) and Institute for energy research (UJVR), has been granted. In addition, Simon Roussanaly stayed in Pittsburgh for seven weeks to collaborate with Edward Rubin and Haibo Zhai from Carnegie Mellon University on membrane separation which has also been the opportunity to discuss with people from NETL and the CCSI project.
- The work and results has been presented at international conferences and for BIGCCS partners. In particular, two presentations on membrane CO_2 capture and CCS from Norcem took place at the 8th Trondheim Conference on Carbon Capture and Storage and a presentation of the membrane work was also given at the 2015 Pittsburgh Coal Conference.

HIGHLIGHT

New approach to design and optimize membrane based CO_2 capture

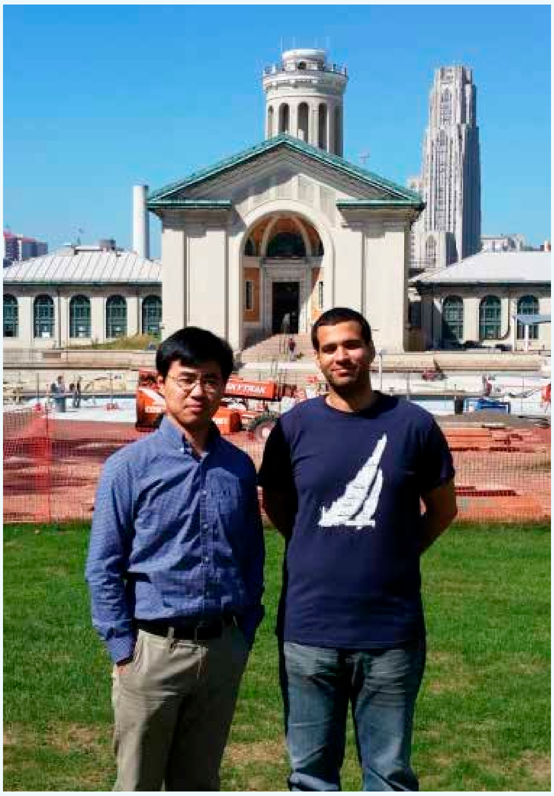
Electricity generation from coal represents respectively 41% and 30% of the world and European electricity generation. CCS from coal power production is considered to be a promising way to reduce CO_2 emissions and decrease the climate impact of power generation across the world.

Promising technologies for CO_2 capture such as membrane are been investigated within the BIGGCS FME centre. In cooperation between SP4 and SP1, a new approach to design and optimize membrane based CO_2 capture has been developed by Karl Lindqvist, Rahul Anantharaman, and Simon Roussanaly from SINTEF Energy Research. The "attainable region approach" was shown to provide membrane capture processes design that is more energy and cost efficient than the classical approach.

Promising technologies for CO_2 capture such as membrane are been investigated within the BIGGCS FME centre

Collaboration with Carnegie Mellon University (Pittsburgh PA, USA) which is one of the top US universities was initiated. The aim of this collaboration is to use the new approach developed by SINTEF ER in order to identify membrane properties that are required for membrane capture processes to be competitive with respect to commercially available capture technology.

As part of this collaboration Simon Roussanaly, Researcher at SINTEF Energy Research, was visiting for seven weeks professors Haibo Zhai and Edward Rubin at Engineering and Public Policy department of Carnegie Mellon University. The results of the collaboration were presented at the 2015 Pittsburgh Coal Conference and will be published as a journal article during 2016.



Haibo Zhai and Simon Roussanaly on the Carnegie Mellon University campus.

INNOVATION AND INDUSTRY BENEFITS

BIGCCS SP4 value chain has developed a methodology and tool for integrated multi-criteria assessment of CCS value chains: The iCCS tool (TRL level 5).

Each element in the CCS chain (capture, transport and storage) is often sub-optimized based on anticipated requirements at the interfaces with other elements. The sum of such sub-optimized chain elements will not necessarily represent the cost optimum for the whole chain. In our methodology, the CCS chain is optimised as one integrated system with a certain degree of freedom in the interface conditions in order to un-lock any potential cost reductions due to synergies and trade-offs between the particular chain elements. This comprehensive integrated techno-economic analysis of the whole chain enables us to identify the minimum cost chain design and provides us with deep understanding of the technical and economic implications of the different technology choices, their performances, and the interface specifications. The design and techno-economic analysis of all chain operations in our tool is based on input from detailed modeling of all governing physical phenomena and on robust and reliable models for thermo-physical properties of real CO_2 mixtures with impurities.

> ... provides us with deep understanding of the technical and economic implications of the different technology choices, their performances, and the interface specifications.

Examples of some of the numerous benefits of such an integrated and at the same time fundamentally sound approach are:

1) Identification of the techno-economic optimal design and operation of each specific element of the chain and the whole chain;
2) Evaluation of potential cost reductions due to synergies and trade-offs between the chain elements and due to increased fundamental knowledge on the CO_2 stream behaviour and process performance;
3) Increased knowledge on the acceptable levels of impurities for the different operations along the chain and the desired levels of impurities from the economical perspectives;
4) Identified trade-offs between the cost of additional cleaning and the additional costs associated with impurities transport, injection, and storage;
5) Feedback to technology developers on the capture, transport and injection design criteria (input and output specifications, and performance requirements) based on cost-optimal overall chain design;
6) Decision basis in form of framework and data enabling evaluation, comparison, and ranking of various CCS chain alternatives.

The comprehensive and consistent methodology and tool developed 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.

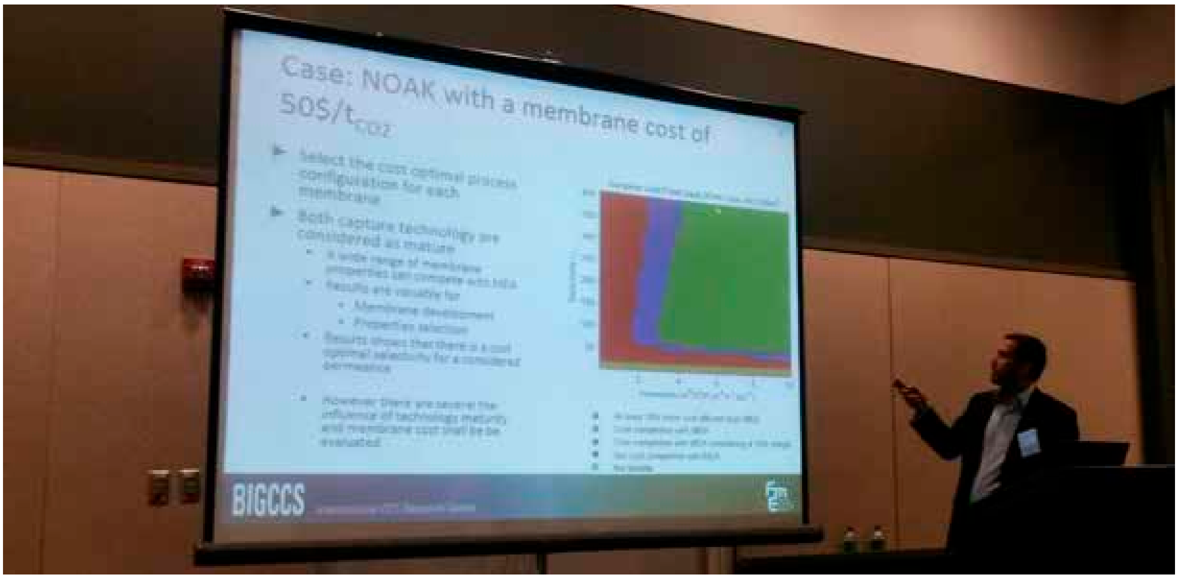
ACADEMIC ACHIEVEMENTS

SP4 submitted three papers in 2015 which will be published in 2016:

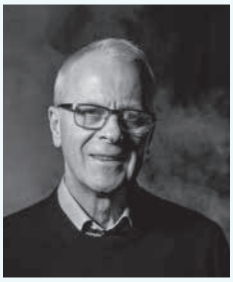
- *Membrane properties required for post-^{c}ombustion CO_2 capture at coal-fired power plants,* Simon Roussanaly, Rahul Anantharaman, Lindqvist Karl, Haibo Zhai, and Edward Rubin, Submitted to Journal of Membrane Science.
- *Cost-optimal CO_2 capture ratio for membrane-based capture from different CO_2 sources,* Simon Roussanaly and Rahul Anantharaman, Submitted to Energy Conversion and Management
- *A techno-economic case study of CO_2 capture, transport and storage chain from a cement plant in Norway,* Jana Jakobsen, Simon Roussanaly, Rahul Anantharaman, Liv Bjerge, Submitted to Journal of Cleaner Production

SP4 work was presented at four occasions in 2015:

- *Value chain analysis of CCS from a cement plant – A Norwegian case study.* Jakobsen, Jana Poplsteinova; Roussanaly, Simon; Bjerge, Liv., 8th Trondheim Conference on Carbon Capture and Storage conference
- *A value chain approach of Carbon Capture and Storage from power generation and Industry.* Jakobsen, Jana Poplsteinova; Roussanaly, Simon; Brunsvold, Amy; Anantharaman, Rahul., Invited lecture at Carnegie Mellon University Department of Engineering and Public Policy; 2015-09-28
- *Membrane properties required for post-combustion CO_2 capture at coal-fired power plants.* Roussanaly, Simon; Anantharaman, Rahul; Lindqvist, Karl Erik Artur; Jakobsen, Jana Poplsteinova; Zhai, Haibo; Rubin, Edward M., Pittsburgh Coal Conference
- *Membrane properties required for post-combustion CO_2 capture at coal-fired power plants.* Roussanaly, Simon; Anantharaman, Rahul; Lindqvist, Karl Erik Artur; Jakobsen, Jana Poplsteinova; Zhai, Haibo; Rubin, Edward M., 8th Trondheim Carbon Capture and Storage Conference



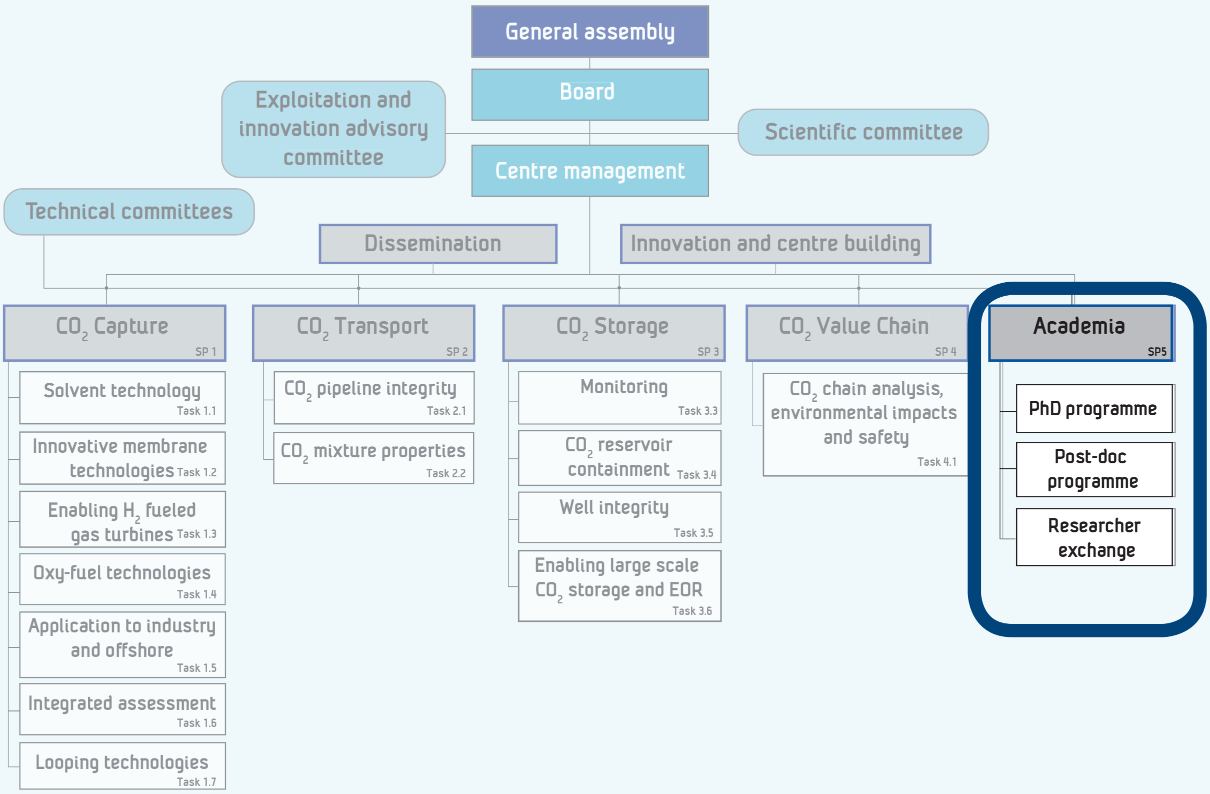
Simon Roussanaly giving his presentation at the 2015 Pittsburg Coal Conference.



Truls Gundersen

Academia and recruitment (SP5)

Despite the fact that BIGCCS is entering its last years of operation, 2015 was still a busy year. By the end of the year, 26 (or 76.5%) of a total of 34 researchers had completed their tasks in BIGCCS, and this of course affects the academic production.



Status by the end of 2015

- 20 PhDs have completed their degrees (six are still active)
- 6 Post.docs have completed their tasks (two are still active)
- 52 MSc Candidates have had their theses related to CCS and BIGCCS
- 98 Journal Articles have been published
- 138 Conference Presentations have been made (not counting internal meetings)
- 12 Countries are represented in our truly international work force of PhDs and Post.docs

What happened in 2015?

- 5 PhDs successfully defended their doctoral degrees
- 15 Journal Articles were published
- 16 Conference Presentations were made
- 2 Post.doc positions were used to fund 1 PhD who started in 2015
- 1 Post.doc was recruited
- CLIMIT's PhD Seminar was arranged in collaboration with BIGCCS and took place in Trondheim September 23–24 combined with BIGCCS Consortium Day. Good participation including some of our partners, and high quality presentations

Gender Issues

- 24% of our PhDs/Post.docs are females
- 38% of our MSc Candidates are females

"Destiny" of our researchers

- Of the 26 that have completed their tasks in, four have either not been able to find a suitable job, or their destiny is "unknown".
- 16 of our researchers were recruited to jobs in Norway (five from Norway, five from Iran, three from China, one from France, one from Poland and one from Bangladesh)
- 5 researchers were recruited by NTNU, four by Statoil and two by SINTEF Energy Research
- 6 have been recruited outside Norway (two in Germany, two in USA, one in Poland and one in China)

What about the future?

- 3 more PhDs are planning to finish in 2016, two in 2017 and one in 2018
- 1 Post.doc will finish in 2016, and one will finish in 2017

PhDs completed in 2015


Marcin Dutka


Nina Enaasen Flø


Espen Birger Raknes


Rengarajan Soundararajan


Amir Taheri

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)

Six nations are currently represented, including the industrial participants Engie (France/ Norway), Gassco (Norway), TOTAL (France/ Norway), Shell (Netherlands/Norway), Statoil (Norway) and the research institutes DLR (Germany), TUM (Germany), GEUS (Denmark), and BGS (UK).

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 has continued 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 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 re- search facilities.
- *The Impact of the Quality of CO_2 and Storage* Behaviour (IMPACTS). A FP7 project led by SINTEF that works to close critical knowledge gaps related to transport and storage.
- *CEMCAP* is a project funded by Horizon 2020 addressing CO_2 capture from cement production. The objective of CEMCAP is to prepare the ground for large-scale implementation of CO_2 capture in the European cement industry.
- *Gateway* is funded by Horizon 2020 and works for accelerating a shift towards deployment of CCS in Europe through a cross-border CO_2 transport infrastructure.

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
- Lawrence Livermore National Laboratory

Organization of conferences, workshops and seminars

On behalf of SINTEF and NTNU, BIGCCS is the organizer of the Trondheim Conference (TCCS) series. The last conference was held June 16-18, 2015 (see chapter on Communication and Dissemination). The TCCS is established as a leading scientific CCS conference. The next conference, TCCS-9, will be held in June 2017, and preparations have already started.

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 industry, the research community, 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 2015.

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 2015. Figures are extracted from the Cristin database.

Publication type:

- Journal publication: 25
- Part of books: 5
- Report/thesis: 7
- Scientific conferences and posters: 59
- Media contributions: 25
- Information material/blogs: 29

Publication/communication channels

Web

BIGCCS launched a new website in 2014. In co-operation with the #SINTEFenergy blog, 39 news stories and blogs were published in 2015.

Blogs

BIGCCS contributed with 33 blogs in 2015. The blogs were about the COP21 in Paris, meeting in Japan, CO_2 storage, CO_2 transport, CO_2 mix, TCCS-8 and more.

Here is a selection from #SINTEF Energy blog:

The Paris Agreement: We got a deal!

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Des	Tot
2014					424	1035	517	986	974	1388	1633	1208	8165
2015	774	1089	1102	1002	1074	1058	684	806	1098	1061	997	862	11607

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

CO_2 impurities: What else is there in CO_2 except CO_2?

Carbon negative oil – fact or fiction?

TCCS-8: The take-home message

Simulating running ductile fracture in CO_2 pipelines

TCCS-8 Conference

The 8th Trondheim Conference on CO_2 Capture, Transport and Storage was opened by SINTEF's vice president for climate technologies, Dr Nils A. Røkke, on June 17. Dr Røkke was proud to emphasize the conference's scientific level. He pointed to CCS as a vital technology to limit the global warming to two degrees.

The 2015 conference had 350 delegates from 26 countries, and comprehensive programme highlighting CCS science. This included 138 oral presentations with 10 keynote presentations and six parallel sessions. Also, more than 100 posters was presented.

After the conference, participants were offered the possibility to publish full scientific papers. Altogether 52 papers were submitted and issued in Energy Procedia, Volume 86, in January 2016.

Member of the Norwegian Parliament, Nikolai Astrup, explained how the Norwegian Government works with CCS.

Dr Hwansoo Chung of Korea's CCS Research Centre gave an overview of Korea's detailed plans for CCS deployment.

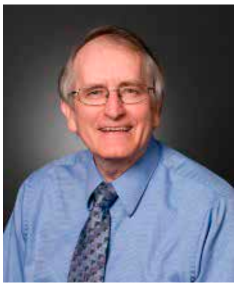
Max Ball, manager of clean coal technology at SaskPower in Canada, gave a status report on the full-scale thermal powerplant with CCS at Boundary Dam.

– The TCCS conference is here for us to keep up the pace, Mona J. Mølnvik. *(All photos from TCCS-8: SINTEF/Svend Tollak Munkejord)*

The SINTEF and NTNU CCS Award

Professor Gary T. Rochelle of University of Texas at Austin was given the SINTEF and NTNU CCS Award 2015. He received the award for his long-lasting contributions within CO_2 capture, in particular for his efforts in development of post-combustion technologies. The award ceremony was held at the banquet of the eight "Trondheim Conference of CO_2 Capture, Transport and Storage" (TCCS-8) on June 17.

Gary T. Rochelle is Professor in chemical engineering at the McKetta Department of Chemical Engineering, The University of Texas at Austin. His wide range of research activities includes: control of air pollution by acid gases, carbon dioxide, and air toxics, CO_2 capture, flue gas desulfurization, acid gas treating, CO_2 mass transfer with chemical reaction, electrolyte thermodynamics, and reaction kinetics in aqueous solutions. He received the SINTEF and NTNU CCS Award for his contributions within CO_2 capture.

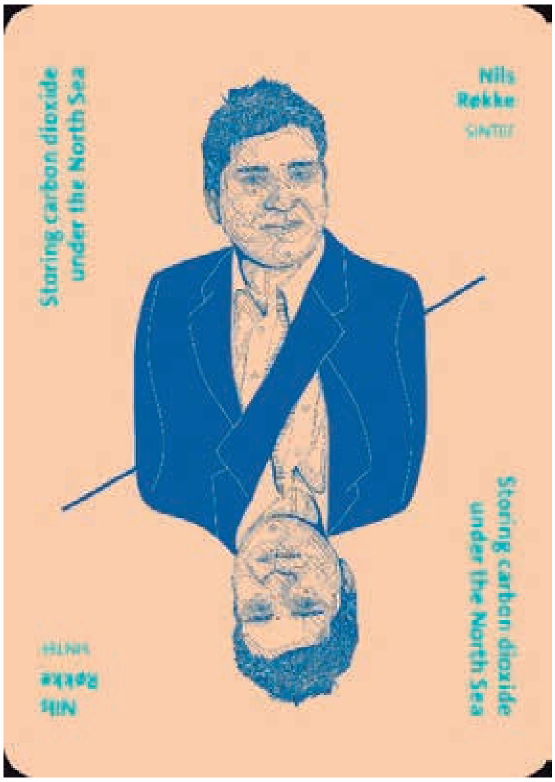


Professor Gary T. Rochelle

COP21: Storing CO_2 in the North Sea

BIGCCS Chairman of the Board, Nils A. Røkke, participated at the United Nations climate negotiations (COP21) in Paris in December. He engaged in side-events on CCS together with British Geological Survey and The Bellona Foundation among others. He wrote a blog from each day in Paris, which can be found on the BIGCCS website *(http://bigccs.no)*.

Preparing for COP21, Nils A. Røkke gave a lecture for Tine Sundtoft, the Minister of Climate and Environment during Arendalsuka in August. This event was organised by The Research Council of Norway. The Minister, who led the Norwegian delegation in Paris, received a card explaining why we need to store carbon dioxide under the North Sea. During the Paris negotiations, the Minister said to a national newspaper, VG, she was positive towards this suggestion.



Media contributions

Nils A. Røkke, in particular, was visible in Norwegian media in 2015. Here are a few examples:

Må gjøre gassen klimanøytral

Regjeringens strategi for CO_2-håndtering (CCS) burde ha handlet om å gjøre norsk gasseksport klimanøytral.

Europas energisektor blir stadig grønnere, og verdensdelens største økonomi – Tyskland – er fyrtårnet. Landet produserer nå så mye fornybar energi at hele forretningsmodellen med jevn produksjon fra kullkraft er utdatert.

Nylig vedtok den tyske regjeringen at landets utslipp av klimagasser skal reduseres med 40 prosent innen 2020. Dette for å bøte på de økte utslippene som skyldes utfasingen av kjerne-

Nils A. Røkke, klimadirektør i Sintef

kraft. Flere kraftselskap på kontinentet innser nå at verdier i kull og kullkraft står på spill.

For Norge innebærer alt dette både trusler og muligheter.

Til nå har Norge kjørt på med norsk gass som et tiltak mot klimakrisen – ved å vise til at gasskraft gir om lag halvparten av utslippene fra kullkraft. Men dette er halvparten av noe som ikke vil være der i fremtiden. Europeiske kullkraftverk kommer nemlig før eller senere til å ta i bruk CO_2-fangst og lagring. Det er simpelthen ikke plass innenfor utslippsgrensene til kull uten rensing.

Kullkraftverk med CO_2-fangst og lagring vil slippe ut kun en tredjedel av CO_2-mengden som vanlige gasskraftverk avgir. Rensing i kullsektoren vil dermed gjøre dagens klimaargument fra gasselgerne ugyldig. Gasskraft med CO_2-håndtering vil imidlertid ha under halvparten av utslippene fra renset kullkraft.

Det nye Europa vil trenge …

… klimanøytral. En slik forvandling ville sikre verdiene i norske gassreservoar, spare klimaet for …

Gasskraftverk er en velegnet strømkilde som kan kobles raskt inn når solen …

Det nye Europa vil trenge energien fra Norges årlige 100 milliarder standardkubikkmeter med eksportgass, men vil ikke ha CO_2-skyen på 240 millioner tonn som følger med, skriver artikkelforfatteren. Her Kårstø prosessanlegg i Nord-Rogaland, som håndterer levering av norsk gass til Europa. Foto: Tomas Alf Larsen

Klima
Nils A. Røkke

Norge bør ta initiativ som kan gi Europa et transport- og lagringsnett for CO_2 i Norskehavet og Nordsjøen

Op-ed, Dagens Næringsliv, February 3: On how the Norwegian government should work towards climate neutral natural gas.

Above: December 12: An historic agreement, Nils A. Røkke said about the Climate deal in Paris, to Adressa.no.

Left: Nils A. Røkke was live on national TV on December 5, talking about COP21.

CLIMIT 10 years

CLIMIT celebrated its 10 year anniversary in 2015, and in that connection three video presentations were produced with central BIGCCS researchers: Svend Tollak Munkejord, Malin Torsæter and Nils Anders Røkke (in Norwegian). The videos can be found at the CLIMIT website: *http://future.climit.no.*

Newsletter

The BIGCCS Newsletter gives information about the latest Centre developments. During 2015, eight issues were produced and e-mailed to ca 350 subscribers. The newsletter typically provides short introductions to the news and happenings, and provides links to full articles on the web. Subscription is open also to individuals not being partners in BIGCCS.

Technical meetings

The technical meeting is the arena where the BIGCCS researchers meet with the partner experts, and is consequently, one of the most important channels for communication of results and discussion of technical issues. During 2015, most of the 14 BIGCCS research tasks organized two technical meetings each. Most meetings were held via telephone or video.

Consortium Day

The BIGCCS Consortium Day 2015 was held at Radisson Blu Royal Garden Hotel, Trondheim on September 22-23. More than 40 participants attended the event, which focused on BIGCCS innovations and potentials for industry take-aways.

In addition to presentations of selected innovations by subprogram- and task leaders, the program offered two interesting presentations from industry members. Dr. Per Ivar Karstad of Statoil shared with the audience Statoil's views on "New Energy Solutions", while Prof. Niels Peter Christensen (Gassnova) presented results from Gassnova's report on potential full-scale CCS projects in Norway (the pre-feasibility study).

In addition to well-prepared oral presentations, and to offer a background for discussions on in-depth technical issues, BIGCCS researchers had prepared more than 30 posters. The poster sessions turned out to be a very successful part of the program.

Poster session at Consortium Day 2015. Dr. Rahul Anantharaman explains details to Chairman of the BIGCCS General Assembly, Ole Kristian Sollie (Shell).

In summing up the BIGCCS Consortium Day 2015, Centre Director, Dr. Mona J. Mølnvik underlined that the CCS activity level is now increasing and that full-scale projects are coming. In this respect, BIGCCS has proved to be an important tool in generating new CCS knowledge, which is, and will continue to be valuable in deployment of CCS technologies.

Webinars

As a means to reaching out to partners with results, BIGCCS will in 2016 offer to its partners a series of webinars. Planning of this activity started in 2015, and the first webinars will be held in April 2016. Participation will be open only for BIGCCS partners. More information can be found on the BIGCCS web.

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, thermophysical 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 understanding 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.

During 2015, no HSE reports directly related to BIGCCS activities were registered. The incidents/deviations listed below are related to laboratory and/or facilities, which have also been used by BIGCCS. Consequently, none of the incidents/deviations are related to BIGCCS activities.

Damage to plants or equipment:

- During mounting of an extruder in the laboratory, it was necessary to tilt the barrel to home position. During this operation, a pressure sensor wire was squeezed, as the wire at this stage is hanging on the side of the barrel. This was not visible from the command post, and the screw from the pressure sensor was damaged. The work was carried on with a different extruder, and the damage was repaired.

Unexpected halting of production or processes:

- Due to a power failure, a problem occurred with the control unit for the ventilation in a clean room laboratory, and the humidifier was switched on while the fan for the air inlet was off. This led to steam being produced over a longer period of time and not being led in to the clean room. The steam spread through the airshaft where it condensed and caused a water leakage. This halted production for approximately 20 days.
- The humidifier to the clean room laboratory was malfunctioning and needed maintenance. As this was not expected, some spare parts had to be ordered, and this caused the humidifier to be out of order for a couple of weeks. To avoid a similar halt in the future, a service agreement is considered. The incident caused a delay in progress of all projects using this lab.

Near misses:

- Leakage from an H2 gas cylinder after working hours. The cylinder was placed in a specially designed cabinet, EX-secured, and the leakage did thus not cause damage or harm to health. The cause of the leakage was that the regulator was not according to the specifications needed for this particular operation, and the regulator was changed.

Dangerous conditions:

- The laboratory ventilation was shut down during maintenance without informing the laboratory personnel. According to procedure, all personnel should be informed of shut down of critical infrastructure. The loss of ventilation did not cause any dangerous situation in this case, but any future incidents like this must be avoided. The procedure of information in case of shut-down of critical infrastructure has been revised with the department responsible for maintenance.

Quality deviations:

- The gas alarm for H2 was triggered and the panel showed that 21 % LEL was detected.

No ongoing operations was using H2 and no leakage from the H2 gas cylinder was shown when investigating with a hand-held detector. The alarm was thus concluded to be false.

SINTEF HSE campaign

For SINTEF as a whole, the safety campaign "Bry deg!" (Care!) was a major undertaking in 2015. The background for the campaign was a negative development in personnel injuries and absence caused by injuries up until 2013.

The main objective of the campaign was to strengthen the safety culture at SINTEF, and furthermore to make responsible and inspire leaders and all other individuals to constructive efforts with the aim of strengthening safety in everyday life. The campaign, involving all staff, has generated commitment, new knowledge and increased awareness of risk issues in the local work environments. The campaign is followed up with concrete HSE plans and actions in all departments. All BIGCCS personnel at SINTEF participated in the campaign.

People

NAME	AFFILIATION	DEGREE	SEX	POSITION
BIGCCS management				
Mona J. Mølnvik	SINTEF Energy Research	PhD	F	Research director
Nils A. Røkke	SINTEF Energy Research	PhD	M	Vice-president
Centre management team				
Anne Steenstrup-Duch	SINTEF Energy Research	MA	F	Communication Manager
Rune Aarlien	SINTEF Energy Research	PhD	M	Centre Manager
Jon Magne Johansen	SINTEF Energy Research	MSc	M	Operations Manager
CO_2 capture (SP1)				
Andrea Gruber	SINTEF Energy Research	PhD	M	Senior research scientist
Anna Lind	SINTEF Materials and Chemistry	PhD	F	Research scientist
Annett Thøgersen	SINTEF Materials and Chemistry	PhD	F	Research scientist
Aud I Spjelkavik	SINTEF Materials and Chemistry	BSc	F	Senior engineer
Bjørnar Arstad	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Christelle Denonville	SINTEF Materials and Chemistry	MSc	F	Research scientist
Christian Simon	SINTEF Materials and Chemistry	PhD	M	Research director
Chao Fu	SINTEF Energy Research	PhD	M	Research scientist
David Berstad	SINTEF Energy Research	MSc	M	Research scientist
Geir Haugen	SINTEF Materials and Chemistry	MSc	M	Research scientist
Hanne Kvamsdal	SINTEF Materials and Chemistry	PhD	F	Senior research scientist
Håkon Ottar Nordhagen	SINTEF Materials and Chemistry	PhD	M	Research scientist
Inge Saanum	SINTEF Energy Research	PhD	M	Research scientist
Inna Kim	SINTEF Materials and Chemistry	PhD	F	Research scientist
Jonathan Polfus	SINTEF Materials and Chemistry	PhD	M	Research scientist
Kari Anne Andreassen	SINTEF Materials and Chemistry	BSc	F	Senior engineer
Karl Anders Hoff	SINTEF Materials and Chemistry	PhD	M	Senior scientist
Kjell Wiik	NTNU	PhD	M	Professor

Knut Thorshaug	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Kristin Jordal	SINTEF Energy Research	PhD	F	Senior research scientist
Mari Voldsund	SINTEF Energy Research	PhD	F	Research Scientist
Marie-Laure Fontaine	SINTEF Materials and Chemistry	PhD	F	Senior research scientist
Mario Ditaranto	SINTEF Energy Research	PhD	M	Research manager
Martin Fleissner Sundin	SINTEF Materials and Chemistry	PhD	M	Research scientist
Mehdi Pishahang	SINTEF Materials and Chemistry	PhD	M	Research scientist
Nicolas Rival	SINTEF Materials and Chemistry	PhD	M	Research scientist
Nils Erland L. Haugen	SINTEF Energy Research	PhD	M	Research scientist
Ove Darell	SINTEF Materials and Chemistry	BSc	M	Engineer
Partow P. Henriksen	SINTEF Materials and Chemistry	PhD	F	Research director
Rahul Anantharaman	SINTEF Energy Research	PhD	M	Research scientist
Richard Blom	SINTEF Materials and Chemistry	PhD	M	Research director
Sigurd Sannan	SINTEF Energy Research	PhD	M	Research scientist
Thijs Peters	SINTEF Materials and Chemistry	PhD	M	Senior scientist
Thor Mejdell	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Tommy Mokkelbost	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Truls Nordby	UiO	PhD	M	Professor
Ugochukwu Edvin Aronu	SINTEF Materials and Chemistry	PhD	M	Research scientist
Vincent Thoreton	NTNU	PhD	M	Post Doc
Wen Xing	SINTEF Materials and Chemistry	PhD	M	Research scientist
Yngve Larring	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Yuanwei Zhang	NTNU	MSc	M	Student
Øyvind Langørgen	SINTEF Energy Research	MSc	M	Research scientist
Zuoan Li	SINTEF Materials and Chemistry	PhD	M	Research scientist
CO_2 transport (SP2)				
Anders Austegard	SINTEF Energy Research	Dr.ing.	M	Research scientist
Brede Hagen	SINTEF Energy Research	MSc	M	Master of Science
Eskil Aursand	SINTEF Energy Research	MSc	M	Master of Science
H. G. Jacob Stang	SINTEF Energy Research	Dr.ing.	M	Research scientist
Håkon O. Nordhagen	SINTEF Materials and Chemistry	PhD	M	Senior research scientist
Markus Richter	RUB	Dr.ing.	M	Oberingenieur
Morten Hammer	SINTEF Energy Research	PhD	M	Research scientist
Ingrid Snustad	SINTEF Energy Research	MSc	F	Research manager
Roland Span	RUB	Dr.ing.	M	Professor
Sigurd W. Løvseth	SINTEF Energy Research	Dr.ing.	M	Senior scientist
Stéphane Dumoulin	SINTEF Materials and Chemistry	PhD	M	Research scientist
Svend T. Munkejord	SINTEF Energy Research	PhD	M	Chief scientist
CO_2 storage (SP3)				
Alexandre Lavrov	SINTEF Petroleum Research	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 Petroleum Research	PhD	F	Research scientist
Amir Taheri	NTNU	PhD	M	Phd student and Post.doc

Anouar Romdhane	SINTEF Petroleum Research	PhD	M	Research scientist
Carsten Nielsen	GEUS	MSc	M	Reservoir engineer
Claus Kjøller	GEUS	PhD	M	Head of laboratory
Dag Wessel-Berg	SINTEF Petroleum Research	PhD	M	Senior scientist
Erik Lindeberg	SINTEF Petroleum Research	PhD	M	Chief scientist
Ector Querendez	SINTEF Petroleum Research	MSc	M	Research Scientist
Gareth Williams	BGS	PhD	M	Geophysicist
Grethe Tangen	SINTEF Petroleum Research	PhD	F	Senior scientist
Halvor Lund	SINTEF Energy Research	PhD	M	Research scientist
Idar Akervoll	SINTEF Petroleum Research	MSc	M	Senior scientist
James White	BGS	PhD	M	Geophysicist
Jan Åge Stensen	SINTEF Petroleum Research	PhD	M	Researcher
Jelena Todorovic	SINTEF Petroleum Research	PhD	F	Research scientist
John Williams	BGS	BSc	M	Geoscientist
Karen Lyng Anthonsen	GEUS	MSc	F	Geo-engineer
Kamila Gawel	SINTEF Petroleum Research	PhD	F	Research scientist
Lars Erik Walle	SINTEF Petroleum Research	PhD	M	Research scientist
Malin Thorsæter	SINTEF Petroleum Research	PhD	F	Research scientist
Maria Barrio	SINTEF Petroleum Research	PhD	F	Senior Business Developer
Peder Eliasson	SINTEF Petroleum Research	PhD	M	Research manager
Peter Frykman	GEUS	PhD	M	Senior researcher
Pierre Cerasi	SINTEF Petroleum Research	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 Petroleum Research	PhD	M	Senior advisor

CO_2 value chain (SP4)				
Amy Brunsvold	SINTEF Energy Research	PhD	F	Research scientist
Jana P. Jakobsen	SINTEF Energy Research	PHD	F	Senior scientist
Erik Skontorp Hognes	SINTEF Fisheries and Aquaculture	MSc	M	Research scientist
Simon Roussanaly	SINTEF Energy Research	MSc	M	Research scientist

Visiting researchers (foreigners visiting BIGCCS)

Name	Affiliation	Nationality	Sex	Duration	Topic
Xiaodong Sun	China University of Petroleum	China	M	12 months	Least-Squares Reverse Time Migration for CO_2 monitoring

BIGCCS researchers abroad

Name	Visiting	Nationality	Sex	Duration	Topic
Simon Roussanaly	Carnegie Mellom Univ., Pittsburgh, PA, USA	France	M	7 weeks	Studies of membrane capture processes

Post docs with support from BIGCCS

Name	Nationality	Sex	Duration	Topic
Vincent Thoréton	France	M	2014-2016	Chemical Looping Combustion Technologies
Nicolaine Agofack	Cameroon	M	2015-2017	Acoustic core measurements and two-phase flow

PhDs with support from BIGCCS

Name	Nationality	Sex	Duration	Topic
Amir Taheri	Iran	M	2010-2015	Study of Density-Driven-Natural-Convection (DDNC) Mechanism in CO_2 Sequestration in Heterogeneous and Anisotropic Brine Aquifer
Robin Wegge	Germany	M	2010-2016	Speed of sound and density measurements of binary, CO_2-rich mixtures over a wide temperature and pressure range
Nina Enaasen Flø	Norway	F	2011-2015	Modelling and analysis of process dynamics related to post-combustion CO_2 capture
Rengarajan Soundararajan	India	M	2011-2015	Coal based Power Plants using Oxy-combustion for CO_2 Capture: Process Integration Approach to reduce Capture Penalty
Espen Birger Raknes	Norway	M	2011-2015	3D elastic time-lapse full waveform inversion
Marcin Dutka	Poland	M	2012-2015	Studies of Low NOx Burner Technology
Dawid Szewczyk	Poland	M	2012-2016	Rock physics and geomechanical aspects of seismic monitoring of CO_2 storage in the subsurface
Snorre Foss Westman	Norway	M	2013-2016	Experimental investigation of phase equilibria of CO_2 mix-tures relevant for CCS
Sohrab Gheiby	Iran	M	2013-2016	Geomechanical Modelling of CO_2 Injection and Storage
Vera Hoferichter	Germany	F	2013-2016	Experimental Investigations on the Influence of Acoustic Excitations on Flame Flashback during Premixed Hydrogen Combustion in a Model Burner
Gabriel Guerrero Heredia	Mexico	M	2014-2017	Novel Hybrid Membranes for Post-Combustion CO_2 Capture
Christoph Meraner	Germany	M	2015-2017	Investigation of scalability of low NOx combution technology

Master degrees (2010–2015)

SP1 - CO_2 Capture			
Name	**Sex**	**Title**	**Semester**
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 substrates 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
Erik Lien Johnsen	M	Optimization based Design of an IRCC Process	Spring 2011
Elmir Sisic	M	Utilization of Low Temperature Heat in Coal based Power Plants With CO_2 Capture	Fall 2012
Katrin Finke	F	Development and Validation of a Matlab Algorithm to Detect Flame Front from OH-PLIF and PIV Images Of a Turbulent, Premixed Hydrogen Flame	Fall 2014
Linn-Therese Forthun	F	Simulation and Model Verification of the Dynamic and Steady State Behavior of the CO_2 Capture Plant at TCM	Spring 2015
Severin M Reiz	M	CFD Simulations Low NOx Burner	Spring 2015
Kristin Skrebergene	F	New Technologies for Carbon Capture in Hydrogen Production from Fossil Fuels	Spring 2015
Opeyemi Bamigbetan	M	A Systematic Design Methodology for Multicomponent Membrane Systems	Spring 2015
Gina Plahte Helsing	F	Options for Carbon Capture with Storage or Reuse in Waste Incineration Processes	Spring 2015

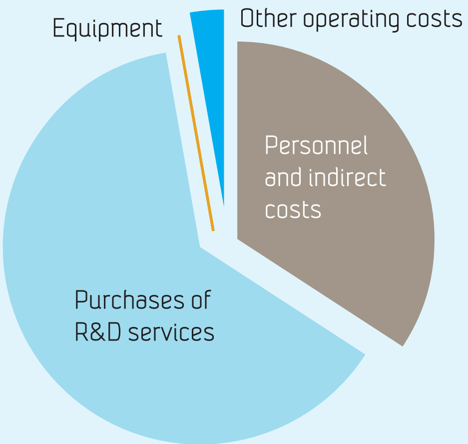
SP2 - CO_2 Transport			
Nicolas Morin	M	Coupled fluid-structure model used for modelling of running fracture in ductile steel pipelines	Fall 2010
Gjermund Haug	M	Running fracture in a H_2 pressurized pipeline: From small scale material testing to full scale experiments and simulations	Spring 2011
Steffen Valheim	M	Running fracture in a H_2 pressurized pipeline: Characterization and simulation of dynamic ductile fracture in two X65 pipeline steels	Spring 2011
Alexander Maurer	M	Commissioning of a single-sinker densimeter and first measurements in CO_2 rich binary mixtures	Spring 2014
Aleksander Reinertsen	M	Models and Numerical Methods for Two-phase Flow of CO_2 in Pipes	Spring 2015

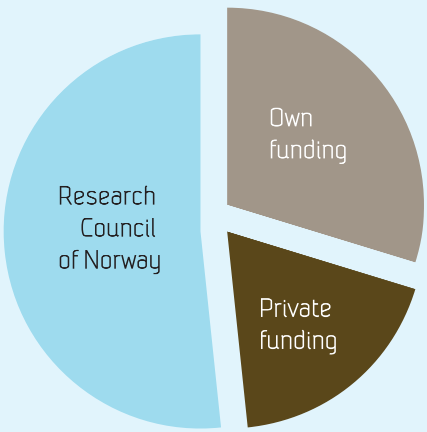
SP3 - CO_2 Storage			
Alberto Perez Garcia	M	Capture, transport and storage of CO_2. Storage cap. study in Spain	Spring 2010
Sissel Grude	F	Sea bed diffractions and impact on 4D seismic data	Spring 2010
Tone Trudeng	F	Sensitivity analysis on the detctability of fractures on 2-D seismic: An early warning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

Financial statement

Actual costs	NOK
Personnel and indirect costs	15 575 475
Purchases of R&D services	28 746 972
Equipment	61 182
Other operating costs	1 152 634
Total	**45 536 263**

Funding	NOK
Own funding	13 658 150
Private funding	8 378 113
Research Council of Norway	23 500 000
Total	**45 536 263**





Publications 2015

Part of book/report

1	**Experimental investigation of cement to rock bonding.** Cerasi, Pierre; Stroisz, Anna Magdalena. I: 49th US Rock Mechanics/Geomechanics Symposium - ARMA. American Rock Mechanics Association (ARMA) 2015 ISBN 978 0 9794975 0 6. p.
2	**Numerical Modeling of Rock Brazilian Test: Effects of Test Configuration and Rock Heterogeneity.** Gheibi, Sohrab; Holt, Rune Martin; Lavrov, Alexandre; Mas Ivars, D. I: 49th US Rock Mechanics/Geomechanics Symposium - ARMA. American Rock Mechanics Association (ARMA) 2015 ISBN 978 0 9794975 0 6. p.
3	**Numerical study of tensile thermal stresses in a casing-cement-rock system with heterogeneities.** Lavrov, Alexandre; Todorovic, Jelena; Torsæter, Malin. I: 49th US Rock Mechanics/Geomechanics Symposium - ARMA. American Rock Mechanics Association (ARMA) 2015 ISBN 978 0 9794975 0 6. p.
4	**SPE-173864-MS Study of Thermal Variations in Wells During CO_2 Injection.** Lund, Halvor; Torsæter, Malin; Munkejord, Svend Tollak. I: SPE Bergen One Day Seminar 2015 - Seminar digital proceedings. Society of Petroleum Engineers 2015 ISBN 978-1-61399-384-2. p.
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6	**BIGCCS - International CCS Research Centre.** Aarlien, Rune. SINTEF-SINOPEC Seminar; 2015-05-08 - 2015-05-08
7	**CO_2 absorption efficiency enhanced by bicarbonate precipitation.** Aronu, Ugochukwu Edwin; Kim, Inna. 8th Trondheim Conference on CO_2 Capture, Transport and Storage, TCCS-8; 2015-06-16 - 2015-06-18
8	**Integration of a precipitating CO_2 capture process in an NGCC power plant.** Aronu, Ugochukwu Edwin; Kim, Inna; Haugen, Geir; Clos, Daniel Perez; Jordal, Kristin. 3rd Post Combustion Capture Conference and SaskPower Symposium; 2015-09-08 - 2015-09-11
9	**In-situ DRIFTS and in-situ XRD studies of CaO and calcined dolomite during CO_2 adsorption-desorption reactions.** Arstad, Bjørnar; Blom, Richard; Lind, Anna Maria; Thorshaug, Knut; Andreassen, Kari Anne. 6th High Temperature Solid Looping Cycles Network Meeting; 2015-09-01 - 2015-09-02
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11	**Chemical and mechanical effect of CO_2 flooding of a sandstone sample.** Cerasi, Pierre; Kjøller, Claus; Sigalas, Lykourgos; Bhuiyan, Mohammad Hossain; Frykman, Peter. The 8th Trondheim Conference on Capture, Transport and Storage; 2015-06-16 - 2015-06-18
12	**Experimental investigation of cement to rock bonding.** Cerasi, Pierre; Stroisz, Anna Magdalena. 49th US Rock Mechanics/Geomechanics Symposium - ARMA; 2015-06-28
13	**Loss of injectivity and formation integrity due to pressure cycling.** Cerasi, Pierre; Walle, Lars Erik. The 8th Trondheim Conference on Capture, Transport and Storage; 2015-06-16 - 2015-06-18
14	**Cements for Safe Plugging of CO_2 Wells Studied by X-ray Tomography.** Chavez Panduro, Elvia Anabela; Torsæter, Malin; Gibaud, Alain; Breiby, Dag Werner. CINEMAX Summer School; 2015-08-24 - 2015-08-28
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31	**Strengthening the CCS knowledgebase - results from International research centre BIGCCS.** Løvseth, Sigurd Weidemann. Workshop "Driving CCS forward in Norway" in annual working and plenary meetings of ISO/TC 265 Carbon dioxide capture, transportation, and geological storage; 2015-09-10
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48	**Lagring av CO_2 i Nord-sjøen.** Røkke, Nils Anders. Arendalsuka; 2015-08-14 - 2015-08-14

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59	**Ensuring well integrity during CO_2 injection.** Torsæter, Malin. CLIMIT SUMMIT 2015; 2015-02-24 - 2015-02-25
60	**From PhD student to researcher - opportunities and challenges.** Torsæter, Malin. CLIMIT PhD day; 2015-09-23 - 2015-09-24
61	**Plugging and abandonment (P&A) research at SINTEF.** Torsæter, Malin. UK-Norway network meeting; 2015-05-20
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Information material

65	**Two weeks until TCCS-8 – an update.** Aarlien, Rune.
66	**Simulating running ductile fracture in CO_2 pipelines.** Aursand, Eskil; Dumoulin, Stephane; Hammer, Morten; Munkejord, Svend Tollak; Nordhagen, Håkon Ottar.
67	**Simulering av løpende sprekk i CO_2-rør.** Aursand, Eskil; Dumoulin, Stephane; Hammer, Morten; Munkejord, Svend Tollak; Nordhagen, Håkon Ottar.
68	**Reiseblogg: I Japan for å finne nye forskningspartnere.** Bolstad, Hans Christian.
69	**CO_2 lagring: Pumpe kald CO_2 ned i den varme sokkelen uten at brønnen går i stykker?** Lund, Halvor.
70	**Hvordan pumpe kald CO_2 ned i den varme sokkelen uten at brønnen går i stykker?** Lund, Halvor.
71	**CLIMIT - Svend Tollak Munkejord (SINTEF) - Om CO_2-transport.** Munkejord, Svend Tollak.
72	**Forsker for sikker håndtering av CO_2.** Munkejord, Svend Tollak.
73	**Hvorfor gode modeller er viktig for sikker og effektiv CO_2-transport.** Munkejord, Svend Tollak.

74	**Models, data and software for safe and efficient CO_2 transport.** Munkejord, Svend Tollak.
75	**Why good models are important for safe and efficient CO_2 transport.** Munkejord, Svend Tollak.
76	**TCCS-8 has started.** Munkejord, Svend Tollak; Mølnvik, Mona J.
77	**BIGCCS – an important contribution to CCS realization.** Mølnvik, Mona J.
78	**TCCS-8: Aligning European Energy Research.** Mølnvik, Mona J.
79	**TCCS-8: The take-home message.** Mølnvik, Mona J.
80	**Vi må lykkes med CO_2 fangst.** Mølnvik, Mona J.
81	**Enabling CO_2 capture from coal power plant using membranes.** Roussanaly, Simon.
82	**Research visit to enable CO_2 capture from coal power plant using membranes.** Roussanaly, Simon.
83	**Workshop to strengthen collaboration between European countries and South Africa on Energy Research.** Roussanaly, Simon.
84	**CLIMIT - Nils A. Røkke (SINTEF) - Om CO_2-håndtering.** Røkke, Nils Anders.
85	**COP21: American Graffiti and Chemical engineers.** Røkke, Nils Anders.
86	**COP21: North Sea – Airbnb for CO_2.** Røkke, Nils Anders.
87	**COP21: Storing carbon dioxide under the North Sea.** Røkke, Nils Anders.
88	**COP21: What's up in Paris?** Røkke, Nils Anders.
89	**COP21: Will it deliver?** Røkke, Nils Anders.
90	**The Paris Agreement: We got a deal!** Røkke, Nils Anders.
91	**CCS is "Big in Japan".** Størset, Sigmund Østtveit.
92	**Carbon negative oil – fact or fiction?** Tangen, Grethe.
93	**Brønnforskning.** Torsæter, Malin.

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94	**Lyttende stein skal gi mer olje. Helsesjekk for stein, basert på bruk av lydbølger, kan øke oljeutvinningen og forenkle planlegging av CO_2 lagre.** Bauer, Andreas; Cerasi, Pierre. Dagens næringsliv [Avis] 2015-01-02
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