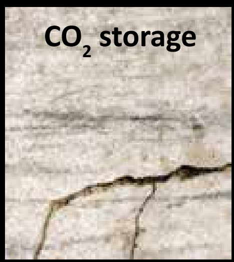

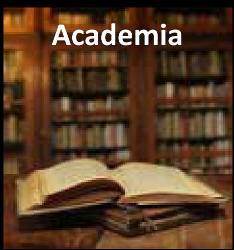

Annual Report 2013

BIGCCS

International CCS Research Centre

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Acronyms:

BGS
Natural Environment Research Council

CICERO
Center for International Climate and Environmental Research – Oslo

DLR
German Aerospace Center

GEUS
Geological Survey of Denmark and Greenland

NGU
Geological Survey of Norway

NTNU
Norwegian University of Science and Technology

RCN
Research Council of Norway

RUB
Ruhr-Universität Bochum

TUM
Technische Universität München

UCB
Berkeley - University of California

UiO
University of Oslo

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Annual Report 2013

BIGCCS Centre - International CCS Research Centre

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Vision and goals

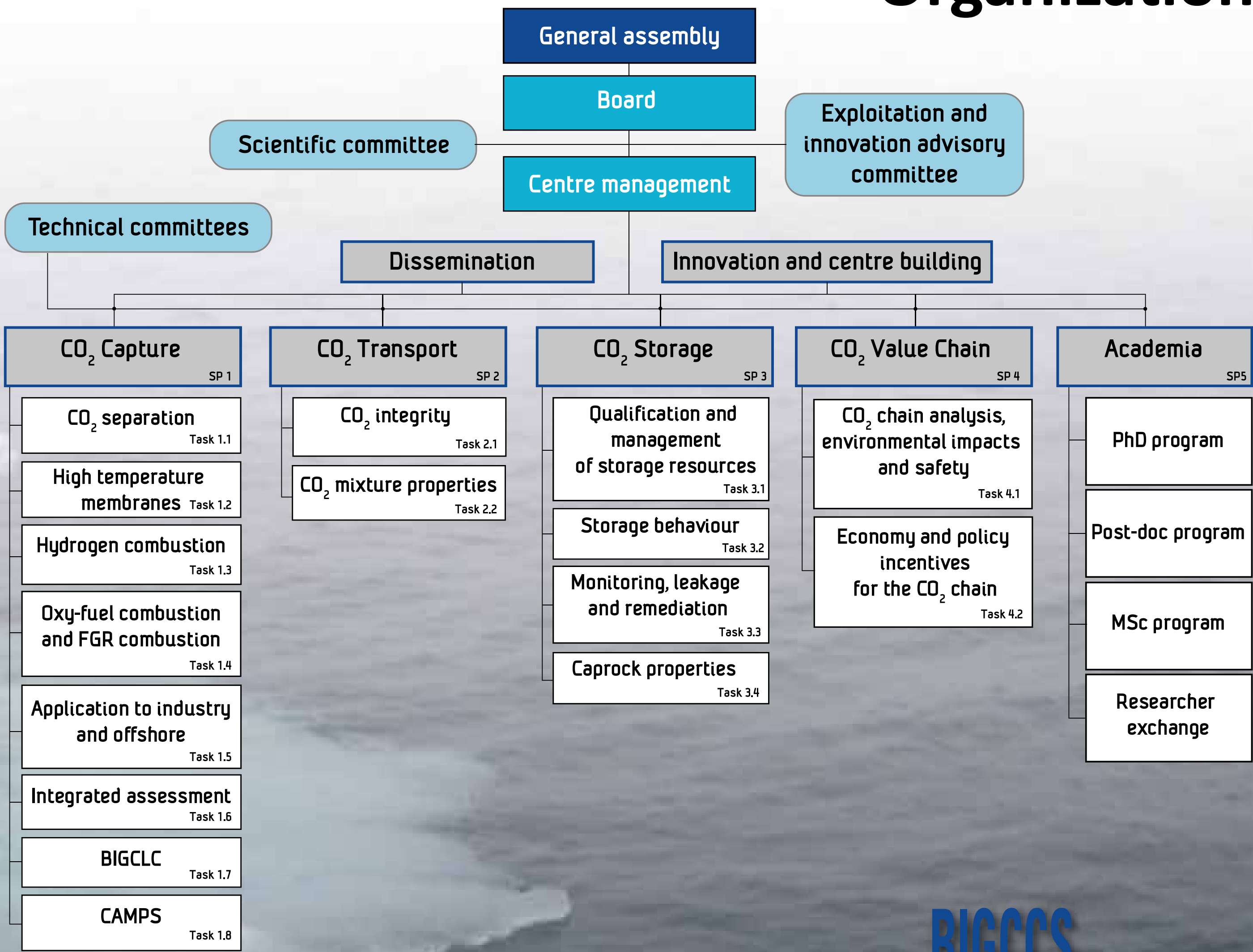
The vision of the BIGCCS Centre is to contribute to the ambitious targets in the Climate Agreement adopted by the Norwegian Parliament in February, 2008.

The BIGCCS Centre will enable 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.

BIGCCS paves 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

Organization



Dear BIGCCS friends

Now, CCS is ready for those who enjoy a challenge - and those who are always looking for opportunities.

Mona J. Mølnvik
Centre Director

2013 was a year of hard work, many achievements, and a feeling of working on a topic that is steadily growing in importance.

The TCCS-7 Conference in Trondheim last summer left a strong impression that the vision of the importance of succeeding with large-scale CCS was confirmed and strengthened among the delegates. Now, CCS is ready for those who enjoy a challenge - and those who are always looking for opportunities.

In 2013, BIGCCS documented its achievements and spin-off project portfolio, which comes to more than one billion NOK. We are now ready for implementation. I believe that the funding agencies in Norway and the EU are beginning to acknowledge this as they see the project proposals for higher Technology Readiness Levels that are arriving from our excellent partners.

BIGCCS passed its Mid-way Evaluation with excellent reviews;

"The Centre shows evidence of being able to continue after year 8."

"The Centre's strong emphasis on covering the whole CCS chain is very important."

"The Centre is well established both nationally and internationally as an important research organisation engaged in fundamental research on CCS, including capture, transport and storage, cooperating with well recognised international research partners. An active and enthusiastic director leads the Centre with strong support from the Board."

"Centre management/members are participating in the EU EERA network on CCS, the ZEP platform, and in the ECCSEL networks. BIGCCS is also participating in the Global CCS Institute from Australia. In this the Centre is engaged in the setting of the international R&D agenda and contributing to the development of the deployment strategy for CCS worldwide."

"The Centre has successfully secured international cooperation with outstanding research groups in Europe and USA. For some of the technologies under development in the Centre this cooperation is essential in order to achieve the ambitious goals."

We have re-structured the work programme of BIGCCS to even better meet the challenges that face the implementation of large-scale CCS. We also support the large-scale CO_2 storage initiative, and current efforts to implement large-scale CO_2 capture in Norway. As this annual report shows, we can point to significant achievements in CO_2 capture, transport, storage and indeed, the entire CCS chain.

Now we are preparing for the next FME call, which will come in 2015. Given the importance of CCS as a measure for meeting the 2-Degree Scenario, the huge CO_2 storage potential on the Norwegian continental shelf and Norway's role as one of the world's largest oil and gas exporters, BIGCCS will be in operation for many years to come.

Sincerely,
Mona J. Mølnvik

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Message from the Chairman of the Board

Europe has fallen behind the US and Canada in deploying CCS and China is picking up momentum. And in Norway we are restructuring our policy to assemble a critical mass for realising this technology.

You may ask why this is happening, hardly anyone claims that we can do without CCS - if we stand behind our promises to curb emissions and maintain a global warming target in the vicinity of two degrees Celsius. This is of course the problem, are we going to maintain our promises?

The recent report from the Directorate of Environment in Norway pinpoints that we are facing a gap of eight million tons of CO_2 in 2020 compared to the Climate Agreement in the Norwegian Parliament. Not deploying CCS seems like going in the wrong direction in terms of meeting our targets.

BIGCCS is supporting the deployment of CCS in power and energy intensive industries. This is important as we must continue to be in the forefront of knowledge and innovation in CCS even though the first plants are delayed.

It is positive to see that EU is now in the process of changing their view on CCS, providing R&D funding for CCS in the new Horizon 2020 programme and reiterates the need for CCS in the recently released "A framework for energy and climate 2020-2030".

The so-called Chris Davies report of the European Parliament strongly supports CCS as a tool for curbing emissions, creating jobs, maintaining a strong industrial base in Europe and improving security of supply. At the same time there are efforts to create a CCS Co-fund under H2020 paving the road for co-operation modes resembling the Berlin model.

In Norway, we are eagerly awaiting the new policy for CCS, how are we going to regain the momentum and make best use of our excellent position in the field.

BIGCCS will be a part of that equation, maybe we can leapfrog the CCS technology and go directly to second or third generation CCS technologies for our deployment. This is a challenge we are happy to address for the CCS value chain and it also points into the future for CCS R&D efforts.

So when will it end? - the seemingly endless debate about if, when and where CCS will be deployed.

Nils A. Røkke
Chairman of the Board

2013 in Review

Tore A. Torp receives the SINTEF and NTNU CCS Award 2013

Joint BIGCCS-CLIMIT PhD seminar

BIGCCS continued adding to its range of activities in 2013. One KPN project on *hybrid membranes and one on chemical looping combustion* were amended, and three additional KPNs were granted by the Research Council. This brings the total volume of the BIGCCS umbrella - the Centre and amended projects - to NOK 580 million!

Like all FMEs, BIGCCS was subject to a midway evaluation. The overall feedback was that the Centre is by now well established nationally and internationally as an important research entity engaged in activities throughout the CCS chain. The Research Council therefore decided to continue funding BIGCCS for the final three years. The evaluation also provided constructive feedback in terms of potential improvements. One result already is the restructuring of some programme activities. Another is that the Centre will focus more on ”high risk - high gain” activities as a basis for increased innovation.

BIGCCS engages in activities along the entire CO_2 value chain. Great emphasis has been placed on interaction between the individual links in the chain. The glue that holds the holistic approach together is the activities conducted by the sub-program *CO_2 Value Chain*, which has been restructured to create an even sharper focus and greater momentum.

In 2013, BIGCCS produced close to 100 publications - mainly conference papers and journal articles – bringing the total number up to 320. The Centre organized the *7th Trondheim CCS Conference* in June, with more than 360 participants from 24 countries, 148 oral presentations and almost 100 posters. At the conference the *SINTEF and NTNU CCS Award* was given to Statoil veteran Tore Torp, for his pioneering role in geological CO2 storage and for his long-lasting contributions to knowledge dissemination. The year also saw a boost in Newsletter production. Seven issues were distributed to more than 300 readers.

Emphasis has been laid on intensifying communication activities with our partners. In particular, the technical meetings conducted via teleconferences have proved successful, with high attendance among the partners. Each BIGCCS task organizes at least two such meetings per year. The *BIGCCS Consortium Day 2013* was s success, attracting more than 30 participants from all partners. This event is particularly important in terms of displaying activities across the whole CCS chain.

The traditional PhD Seminar was jointly organized with the CLIMIT PhD seminar. Almost 60 young researchers attended, and presented many innovative solutions that may very well lead to the next-generation technology needed for worldwide CCS deployment.

BIGCCS continues to reach out to extend cooperation with relevant projects and organizations. On the domestic side, the joint effort with FME SUCCESS continued. The vision is annual storage of 10-100 million tons of CO_2 in sites on the Norwegian continental shelf, and a study has been performed to map the gaps in geoscience and petroleum technology. The CLIMIT program has also commissioned a pilot project by the two FMEs to develop the basis for a national feasibility study on large-scale CO_2 storage, with the aim of determining how and at what cost the vision can be implemented.

There are strong links between the BIGCCS and NORDICCS projects. Funded by the *Top Level Research Initiative* under *Nordic Innovation*, NORDICCS is a virtual network of industrial companies and research organisations. Among the results of this cooperation was the *NORDICCS Summer School* held in August, at which 30 students were given an intensive one-week training course in CCS.

BIGCCS personnel have been actively involved on the international arena. 2013 was an important year in terms of defining processes

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

and decision-making for Horizon 2020, ERANET, EERA, and the Integrated Roadmap of the SET plan. BIGCCS researchers have left solid marks in all these programmes, which will have ramifications for CCS activities in years to come.

The strong focus on HSE issues has been maintained. The primary focus has been on safe laboratory operations, and SINTEF Petroleum Research in particular has intensified its efforts in this area. Four incidents or dangerous conditions were reported, although none of them led to personnel injuries. Routines for field-work will be given priority in the next phase.

Verification of research theories by laboratory experiments is one of BIGCCS' success factors. Continuous renewal and upgrading of laboratory infrastructure is therefore vital. BIGCCS contributed significantly to an ECCSEL application to the Research Council, and the result was NOK 50 million for new infrastructure and another NOK 100 million for upgrading of the CCS laboratory. Advanced test rigs were also installed for characterization of CO_2 mixtures and for chemical looping combustion.

During its fifth year of full operation, BIGCCS has moved into the harvest season. Three PhD candidates completed their degrees – Andrew North and Don Frederick (both UC Berkeley), and Xinzhi Chen (NTNU). Two postdocs also completed their work – Xiangping Zhang and Nousha Kheradmand (both NTNU). By 2013 all of our PhD and postdoc candidates have been recruited.

BIGCCS researchers are also being noticed on the international arena. PhD candidates Sissel Grude and Georg Baumgartner both won international recognition by winning prizes for "best papers/presentations", and researcher David Berstad won a "best paper award".

BIGCCS has delivered a series of important research results in 2013. Among the most promising are:

Capture – Collaboration between sorbent and power process experts shows that the BIGCCS goal of a lower capture penalty than six percentage points can be reached with an integrated natural gas combined cycle with captures by means of Ca-looping. While the reference process without capture has a net efficiency of 58.1 %, the Ca-looping process shows 53.5 % - 4,6 percentage points penalty.

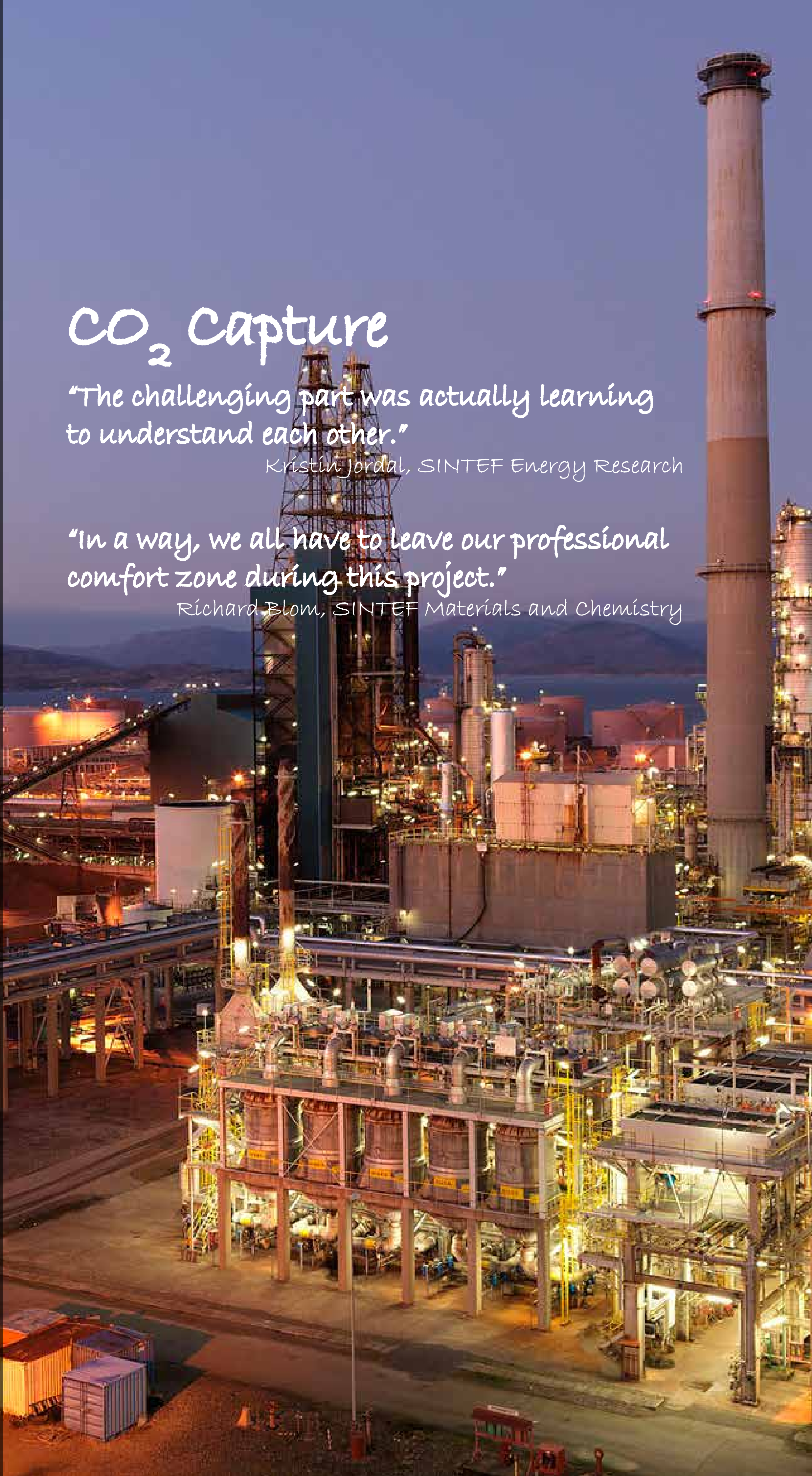
Transport – The CO_2Mix project, which aims to provide high-quality vapour-liquid equilibrium data, has performed unique measurements in a new laboratory test-rig for characterization of CO_2-rich mixtures. New knowledge about the properties of such mixtures is essential for safe capture, transportation, and storage at lower cost, which is required for large-scale CCS. Better property knowledge could enable significant cost savings to be made in areas such as material selection, dimensions, energy use, and flow metering.

Storage – One important achievement has been in the field of mathematical modelling of convective mixing of CO_2 in saline water. The mechanism is caused by the gravitational instability of a diffuse boundary layer. The dissolution of CO_2 in saline water will be an important storage mechanism, but the phenomenon is challenging to analyse with mathematical models. The minimum time for onset of instability has been demonstrated, which is essential for documenting safe CO_2 storage.

Value chains analyses – New models are developed for offshore pipeline and CO_2 shipping transport. They have been used to identify the cost-optimal technology for a wide range of conditions – for instance, quantifying how much pipeline is favoured by large capacity and small distances, and how much CO_2 shipping is favoured by small capacity and long distances. Detailed models to assess techno-economic performance of CO_2 transport technology can lead to significant cost savings through technology selection as well as optimisation of the characteristics of a technology.

New laboratory infrastructure

Seven Newsletters issued in 2013




Partow P. Henriksen


Richard Blom

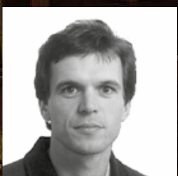

Jonathan Polfus


Andrea Gruber


Mario Ditaranto


Rahul Anantharaman


Kristin Jordal


Øyvind Langørgen


Sigurd Sannan

CO_2 Capture

"The challenging part was actually learning to understand each other."

Kristin Jordal, SINTEF Energy Research

"In a way, we all have to leave our professional comfort zone during this project."

Richard Blom, SINTEF Materials and Chemistry

Temperature and pressure, and leaving your professional comfort zone

"If you can match temperatures and pressures in a clever way, you will be close to solving the capture problem. That is what this is all about", says Kristin Jordal.

As a leader of integrated assessment (Task 1.6) in the Sub-project CO_2 Capture, Kristin Jordal coordinates two quite different fields – each with a language and culture of its own. She represents process technology at SINTEF Energy Research, while Richard Blom's field is sustainable energy technology at SINTEF Materials and Chemistry.

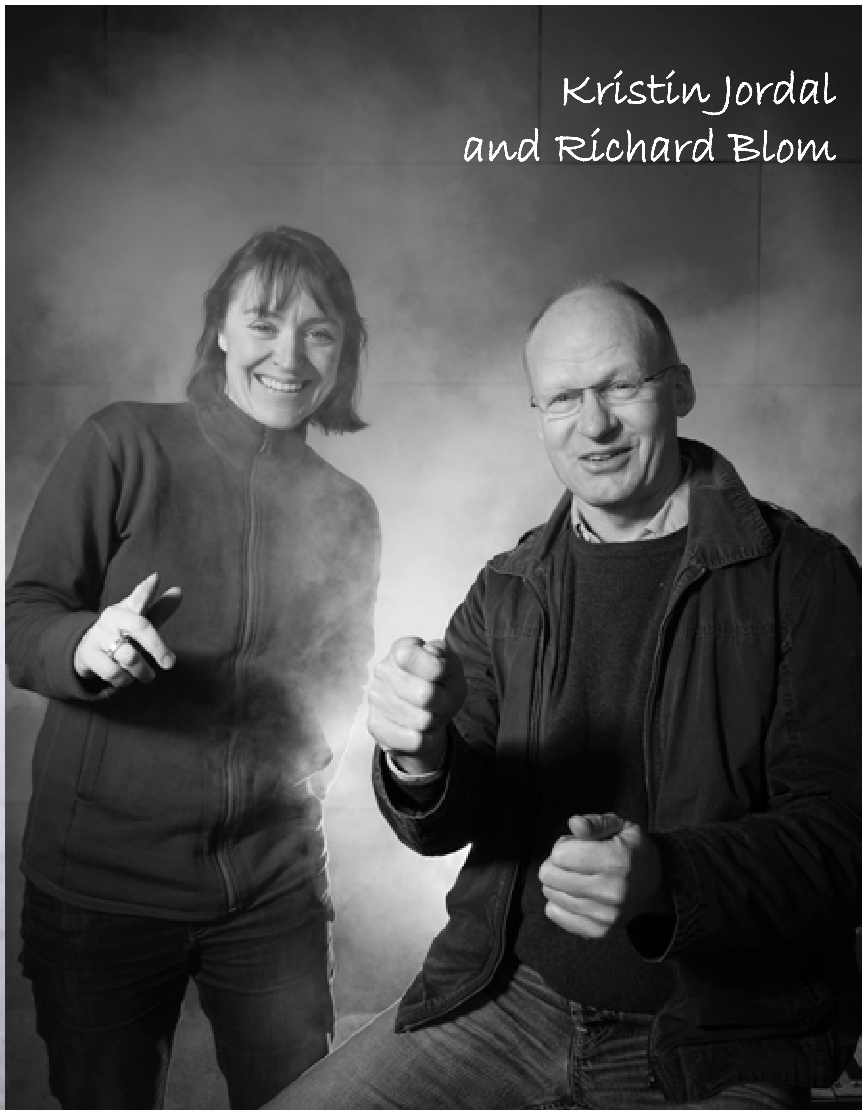
– The good thing about this combination is that it makes us work interdisciplinary, which means that we can get higher quality results. The challenging part is that we do not speak the same scientific language, since we are specialists in different fields. We have to trust each other.

"Hello Richard", says Jordal to her colleague who appears in tiny frame at her computer. Richard Blom is joining us on Skype. They have been working closely on this task – even with 500 km separating them.

Largest cost element

CO_2 capture is the largest cost element in CCS; typically 60-80 % of the total costs. This means that the greatest potential for CCS cost reduction is reducing capital cost and energy consumption in the capture process.

– Our approach is what we call integrated assessment, which means that we evaluate the potential of CO_2 capture technologies (solvents, sorbents, and membranes) based on



unit modeling and process simulations and try to identify the best directions for further research on these capture technologies, says Jordal.

Working together

– We are attacking the problem from two sides – process and material – and we see that our strength is interdisciplinary, says Blom.

– It is crucial to be able to rely on the competence that exists within the BIGCCS researcher family. This is what I like about the Centre concept, says Jordal.

Both Blom and Jordal agree that they cannot just read the literature – the most important road to success is cooperation between scientific fields.

– And to do that properly, we need to ask the right questions of our colleagues, says Jordal, and gives us an example.

– We were looking into calcium looping as a technique to capture the CO_2; it has mainly been investigated for CO_2 capture from coal. No one had investigated it for CO_2 capture from gas-fired power plants. We saw directly that there was a good temperature match between calcium looping and the gas turbine and thought this could be a promising process – but the results we got in the first investigations were not any good. Then we talked to Richard and his colleagues, she says.

– Based on my previous knowledge of the field I did some deeper research into the literature, and I also knew what kind of results we had got from our own experiments on those materials. I also analysed the numbers before they were used in the model that the process technology group had applied to the calcium looping process, says Blom.

Kristin Jordal confirms that the results were so much better in the second round, and it was crucial for them to find the figures that would demonstrate the potential of the calcium looping process with more advanced materials. – Without Richard's analysis we had been unable to do that. He saw immediately that the materials data from the literature that we used in our first simulations represented the poorest imaginable calcium looping material.

– In our fields there are a lot of possible ways of separating CO_2, and we have to compare them in order to find the most promising alternatives, but we cannot study them all at the same time. Every process has its pros and cons, and our task is to give a clear assessment of the potential of each of them, in collaboration with the specialists in different capture technologies. That shows that an interdisciplinary approach is essential in a research Centre like BIGCCS, says Jordal.

Pointing out the direction

The team is working on technologies that don't exist yet, but they have to design models for it anyway and to perform simulations, which is pretty challenging.

– Our goal is to find out as much as possible about the potential of various materials in the capture process; e.g. solvents, sorbents and membranes. We are not going after state-of-the-art solutions, but the real potential, which means we have to take risks in how we approach this. That is also the good thing being in BIGCCS, says Jordal. We have a lot of time compared to other projects I've been on. We have the time to take a detour to find out if there is something in it, rather than just concentrating on the obvious solutions. This has given us an advantage and we now have a good grasp of the calcium looping process.

– We have to trust the figures and numbers provided by others, which once again means that dialogue is important, and that we understand each other, says Jordal.

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– In a way, we all have to leave our professional comfort zone during this project, says Richard Blom, and when we succeed it is twice as satisfying.

– Even though we are working on fundamental material studies, our results will have an influence on how BIGCCS comes out; – from the start of 2014, we will sharpen our focus on the requirements that must be put on CO_2 capture for achieving a 50% reduction in CO_2 capture cost compared to most mature technologies.

Key factor

– Our most successful task so far on a process level is where we are looking into the potential for better efficiency if we use an advanced process with good materials. Better materials are the key factor to improve efficiency in a way that does not make the process more complex. But to make a better material can also be quite complex, says Blom.

– This shows the importance of interdisciplinary efforts, and it is very satisfying to get a better result after you have presented your task to a colleague who works with materials.

Throughout BIGCCS, the conclusions of integrated assessment research have been directly comparable to the tangible objectives of 90% CO_2 capture rate and a fuel-to-electricity penalty of less than 6 per cent.

– We are also working closely with Tasks 1.2 (Membranes) and 1.3 (Hydrogen Combustion), and are looking into a new method for hydrogen combustion", says Jordal.

Leader CO_2 capture:
Partow Pakdel Henriksen
Research Director
SINTEF Materials and Chemistry

Achievements

- A set up has been developed for solid-liquid-vapour equilibrium determination with the capability to monitor precipitation at process condition.
- A dynamic model that represents CO_2 capture plant behaviour at transient condition has been developed.
- Detailed knowledge of Ca-based sorbents has been obtained by in-situ XRD techniques (material studies while reactions are taking place) at relevant industrial conditions.
- Asymmetric tubular hydrogen and oxygen transport membranes (30 cm long) are developed, successfully fabricated, characterized and tested for flux measurements in realistic operating conditions. These membranes suit Pre- and Oxy-combustion CO_2 capture.
- Successful installation of a 100 kW high pressure (10 bar) oxy-combustion facility is achieved.
- A US-Norwegian network for combustion modelling and simulation has been established
- Improved models for describing particle-fluid interaction of porous reacting particles relevant to oxy-combustion concepts are developed.
- Retrofit of fired heaters for H_2 or oxy-combustion has been shown to be feasible and potentially a cost-effective route to CO_2 capture in refineries.
- Design, validation and manufacturing of 150 kW CLC test rig are completed.
- Eight PhD candidates have been hired and some have completed their program.
- 30 peer reviewed publications and 59 presentations and posters are submitted.
- Four spin-off projects in form of CLIMIT KPN have been generated.

CO_2 Transport

"Clean CO_2 we do know well – but when it is mixed with other gases its properties change, which will affect how we finally plan how to transport CO_2."

Sigurd W. Løvseth
SINTEF Energy Research


Svend T. Munkejord


Ingrid Snustad


Håkon Nordhagen


Sigurd Løvseth

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

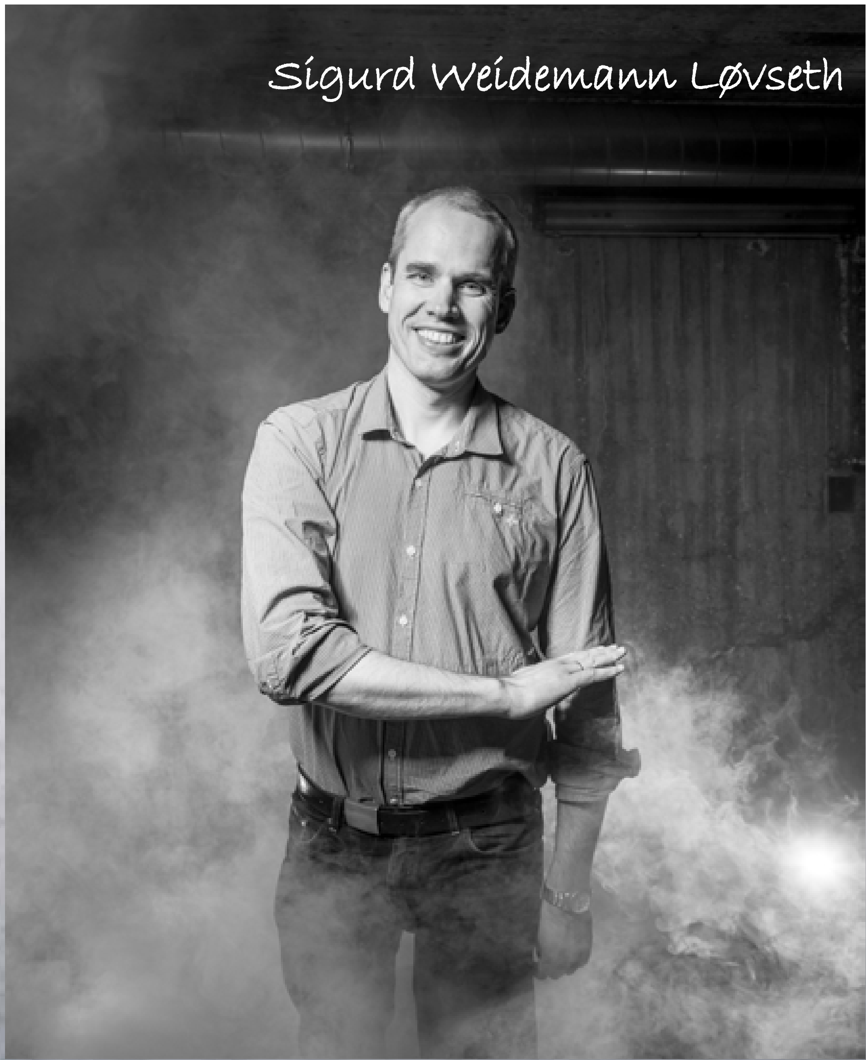
Gaining new insight into CO_2 mixtures

An important aspect of CO_2 capture and storage is transportation from where it is produced to the storage site.

– CO_2 is a well-known gas, but when mixed with other gases it behaves differently than on its own. In order to provide safe transportation, we need to know how small impurities affect the gas, says Sigurd W. Løvseth. Løvseth is a research manager at SINTEF Energy Research, Department of Gas Technology.

– CO_2 captured in a CCS process will never be absolutely pure, but even small quantities of impurities can significantly affect the thermophysical properties of CO_2. Therefore, to be able to design capture processes, transport systems and injection schemes, we need high-quality data for likely impurities in the relevant range of concentrations, pressure, and temperature. There are still several blank areas on the map, and we aim to fill some of them.

Sigurd W. Løvseth explains the big picture before diving in to the details. –Today we transport small amounts of CO_2 for injection on the Sleipner and Snøhvit fields, but in the future the volume will have to be very much bigger and the costs much lower to make CCS financially viable.



Great accuracy

– To get the market for CCS to function it is important to know with great accuracy how the gas behaves when it contains small amounts of impurities. Such numbers does not exist for all conditions today. For instance, we have to know the density of the gas to calculate how much CO_2 is being transported, stored, and hence paid for. We cannot have liquid water in the pipework because it would cause corrosion, so we need to know the conditions under which this would be a problem. For the design of most process equipment and transport infrastructure, knowing whether the fluids are in the gas or liquid phase, or both, is of great importance.

– Clean CO_2 we do know well, but when it is mixed with other gases its properties change, which will affect how we finally plan the transportation of CO_2.

Good results in 2013

– There is no off-the-shelf equipment available to do the measurements to the levels of accuracy and traceability we need, so we are designing and building a unique experimental setup ourselves. This effort has been complicated by the fact that many of the impurities are explosive, corrosive, and/or toxic. In 2013, the first phase-equilibrium measurements were performed, and it was very encouraging to see that this first series of measurements confirmed existing models where these are known to work well, and at the same time provided new insight into conditions under which these models fail, says Løvseth.

This is a collaboration between SINTEF Energy Research, NTNU and the Department of Thermodynamics at Ruhr-Universität Bochum in Germany, led by Professor Roland Span, who is the man behind the established reference equation of state for pure CO_2, the Span-Wagner equation. His group is also well known for its world-class experimental work on properties of gases, and is contributing to the project with measurements of speed of sound and density in CO_2 gas mixtures.

– For us it is crucial to bring the costs down. We cannot afford to build bigger and more expensively than absolutely necessary, because we don't know how the fluids involved will behave. We need very accurate measurements to use in our mathematical models in order to produce results that can be trusted. What we hope to do in BIGCCS is to develop and use models that are traceable and based on certified standards.

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Leader CO_2 transport:
Svend Tollak Munkejord
Chief Scientist
SINTEF Energy Research

Achievements

- A unique coupled fluid-structure fracture-propagation control model for CO_2 pipelines has been developed
- Several experimental set-ups for highly accurate measurements of thermodynamic properties of CO_2-rich mixtures have been constructed:
  - Vapour-liquid equilibrium – now in operation
  - Density
  - Speed of sound
- One PhD completed, two more are well under way
- Seven journal articles, five conference articles and two popular-science articles have been published


Grethe Tangen


Malin Torsæter


Peder Eliasson


Idar Akervoll


Dag Wessel-Berg


Pierre Cerasi


Alv-Arne Grimstad

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CO_2 Storage

It is not as trivial as it might seem.

Pierre Cerasi
SINTEF Petroleum Research

Rock-solid storage

Our overall objective is to provide improved understanding of the fundamental effects of CO2 injection on changes in the geomechanical and sealing properties of a storage reservoir and its cap rock.

The storage part of BIGCCS focuses on developing storage-related issues to a level that will allow safe long-term storage. One of the goals of this part of BIGCCS is to improve current knowledge about the interactions of CO_2 with the storage volumes. This aspect also includes interactions with the sealing formations needed by the storage volumes.

– We are trying to develop guidelines for where and how to select candidate sites for storage; it is rather like giving a stamp of approval, says task leader Pierre Cerasi, a senior researcher at SINTEF Petroleum Research.

It is vital to measure how a well and its surroundings will react when we are injecting liquid CO_2. The pressure rise will stress the rock: the added liquid will push on the pore walls, leading to what scientists call changes in effective stress. We need to know where the biggest stress changes are likely to occur. Only a combination of computer simulations and laboratory testing can do this.

More questions to answer

– We have already done some tests that gave us some answers but also produced a lot of questions. One identified risk is that when we are injecting CO_2 gas or liquid at a certain temperature, the liquid will not be at the same temperature as in its near-well surrounding structures. That could cause trouble in the rock formations adjacent to the injection well. This is something we need to investigate more. How will it affect the rock and the pores regarding storage? asks Cerasi enthusiastically.

Another aspect that needs to be looked into is the sealing rock above the reservoir, where we are trying to figure out how cracks caused by temperature differences develop as a result of the build-up of thermal stress. Obviously, we do not want any leakage of the stored CO_2.

Stress impact

Investigating temperature effects on the integrity of the whole injection well and neighboring rocks is a difficult task in the laboratory. How can relevant tests be run in the limited space available in our compression load frames?

– We wanted to start by isolating parts of this complex system such as the rock alone, in order to study the impact of a small area subjected to stress and temperature on cracks across the layer. The research group decided to cool the rock to see if exposure to cold fluid could generate cracks, but this was not possible with their existing equipment.

– Then they tried to change the specimen geometry and induce cracking by heating; this would be completely equivalent in terms of mechanical analysis. But we couldn't accurately measure this effect because everything around the rock, the load frame's metal elements, also expanded because of the heat. In the end we bought special infra-red lamps, so as to focus heating directly on the rock specimen, without heating the metal parts of the load frame. These tests are ongoing.

According to Pierre Cerasi, this turned out to be a much more complex operation than they thought.

– Our biggest challenge in this task is the limited funding available – but we are using it as best we can. We also want to run a lot of tests, but we have to choose among them, because we don't have the time or the money to do them all. After a while we focused on one part: the fundamental physics and the different properties of different materials. When we have a good understanding of the behaviour of all the components, modelling the composite system becomes possible.

Motivating research

For Cerasi and his colleagues working on this part of the problem is highly motivating.

– We know that our work will guarantee that the CO_2 will stay underground, and that encourages us. Our research, like everything else that is being done in BIGCCS, is taking us a step further towards improving the climate and stopping CO_2 emissions in the future. The most positive aspect is that we get the chance to work alongside other disciplines and research institutes, both in Norway and internationally. We are just at the beginning of doing this; for the first few years we merely investigated the ideas, now we are starting to try things out in pilot studies.

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– The real challenge will come when this moves into really large-scale storage, with the whole of the North Sea shelf acting as a huge storage site. That is why it is important to focus on secure storage, and to choose the best technical solution available. We also need to know how to look for a leakage, and know which tools we will use to seal cracks and prevent the CO_2 from escaping.

Still a long way to go

– But this is still a young area, says Cerasi, and there is a lot of research to be done. Although we already have a great deal of knowledge about how to extract oil from the ground we haven't done the reverse operation yet; pumping CO_2 back into wells and fields again on a large scale, and we need to remember that a reservoir is not a balloon, it is not elastic; extracting the oil/water reduces the pressure within the formation, and it is essential to know what happens when we start to re-inject fluids. And storing CO_2 where oil was not stored before is also a problem in terms of pressure and mechanical stresses. It is not as trivial as it might seem.

Leader CO_2 storage:
Grethe Tangen
Senior Scientist
SINTEF Petroleum Research

Achievements

- Estimation of pressure constraints for CO_2 storage when the cap rock has pre-existing faults
- Showed that water production from the storage formation can significantly increase CO_2 storage capacity and for onshore sites it can enable geothermal energy
- Established the theoretical basis for estimating onset time for diffusion induced convection in the brine column underneath a CO_2 gas cap. A PhD student has confirmed experimentally the parameters controlling onset of convection mixing of CO_2 and brine.
- High-resolution imaging of the Sleipner CO_2 plume with visible thin layers
- Developed and tested two methods for discrimination of pressure and saturation changes
- Developed and used a new experimental methodology for studying cement bonding to rock and revealed that CO_2 leakage along wells can be reduced by using adapted drilling muds.
- A laboratory set-up to investigate leakage risk through reactivated faults, for ultra-slow deformation rates.
- Established a new test procedure for investigating tensile thermal stress due to cooling in rock and cement specimens.
- Close collaboration between BGS, GEUS, NTNU and SINTEF
- Six PhD students, three will finish in 2014. Three postdoc fellowships.

The BIG picture; large-scale storage of CO_2

" If we aim to make a difference in the world regarding the 2 degree goal, we cannot settle for storing 1-2 million tonnes of CO2 a year. We have to think BIG!"

Grethe Tangen
SINTEF Petroleum Research

– The maths doesn't add up without capture and storage of CO_2 , says senior scientist Grethe Tangen confidently. There is no more room for discussion. Now it is time for solutions.

She is deep in the field as a leader of a CO_2 Storage Sub-project. Her team investigates long-term CO_2 containment, management of formation pressure when CO_2 is injected, integrity of CO_2 wells and technologies for monitoring CO_2 in the reservoir.

She also leads another project in collaboration with FME SUCCESS and Gassnova that focuses on the big picture; large-scale storage of CO_2.

– Large-scale storage is a matter of 10-100 million tonnes of CO_2 per year. To make a difference at a global scale, we need to store huge quantities.

Large-scale CO_2 storage calls for large storage sites

There is a growing recognition that we need to scale up CCS deployment to meet the UN and EU climate policy goals. According to the IEA, 2000 million tonnes of CO_2 must be stored every year by 2030, posing tough requirements with regard to storage capacity and efficiency. Global deployment of CCS can be more effectively achieved by scaling up to fewer and larger storage sites, and collecting CO_2 from many capture projects and integrated transport systems.

Norway has few point sources of CO_2, and full-scale CCS from Norwegian industry will mainly impact the national emission accounts. On the other hand, Norway can offer storage capacity at a size relevant to storage of CO_2 piped from European industrial sources. This solution could also resolve the European CCS deadlock caused by public opposition to storing CO_2 onshore.

Common vision

In spite of the current urge to develop low-carbon solutions, it is currently difficult to build the business case for CCS. The cost of reducing CO_2 emissions by far exceeds the cost of emitting CO_2 from the industry processes. As a result, industry is reluctant to invest. Without a clear policy and incentives to stimulate the development of a commercial market nobody will put money on the table to solve the problem. Until that happens, there are few industrial actors that are prepared to challenge the research community to develop the knowledge and technology needed for commercial CO_2 storage.

– So we will just have to be our own motivators, says Grethe Tangen enthusiastically.

– By formulating a common vision for large-scale CO_2 storage on the Norwegian shelf, CCS research can regain its momentum in spite of the current lack of demanding "customers". Many years of CCS research, the experience gained from storing CO_2 from the Sleipner and Snøhvit natural gas fields, our expertise in offshore oil and gas operations, combined with enormous offshore storage capacity, will enable Norway to play a significant role in limiting global CO_2 emissions.

Gaps in knowledge pinpointed

In the course of the past year, major Norwegian research institutions have pinpointed gaps in our knowledge that will have to be closed before large-scale CO_2 storage can be implemented. The main conclusion is that there are no technical showstoppers. However, current technologies must be employed and validated to meet the challenges associated with up-scaling and commercial use. It is also important to investigate non-technical challenges such as business models for developing a large-scale CO_2 infrastructure, regulations and framework conditions.

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Through common efforts to define a strategy for closing the final knowledge gaps, the research community can regain momentum and ensure that the national research project portfolio has a suitable profile. This is essential for the development of safe and cost-efficient solutions for CO_2 storage in time to curb global CO_2 emissions.

Case studies

A plan is being drawn up for a feasibility study based on selected storage sites. The ambition is to employ and further develop the methodologies needed by industry to undertake field development studies by 2018. The case study will provide new understanding of what it takes to store large quantities of CO_2 under the Norwegian shelf, and it may help motivate the authorities to engage in a more forceful schedule for CCS development and deployment. By taking such measures, Norway will also encourage other nations to engage more strongly in attempts to reduce CO_2 emissions through CCS.

On doing research on the right topics

From time to time, we have to stop and ask ourselves a single question: are we doing research on the right topics?

When representatives of the BIGCCS and SUCCESS programmes got together with people from CLIMIT to ask just that question, they got a direction-changing response that resulted in the very exciting project: “Large-scale CO_2 storage on the Norwegian shelf”.

- The challenge in prioritising our R&D efforts lies in the fact that we to a great extent lack the “demanding client” who, in a normal commercial market, is looking for R&D that could solve the problems facing his own company, says Svein Eggen, a senior consultant at Gassnova SF.

“Large-scale CO_2 storage on the Norwegian shelf” was set up with the BIGCCS and SUCCESS research centres, which have just completed a study of CO_2 storage on behalf of CLIMIT.

The study attempted to replace this demanding client with a vision of a central storage site on the Norwegian continental shelf.

- Our thinking is that the challenges involved in establishing, constructing and operating such a “generic” central storage site could help to focus and prioritise our R&D efforts, based on the concrete problems we will face if such a storage site is established before 2020,” says Svein Eggen, adding that this is an important project for CLIMIT.

- The way the problem was solved, based on two large centres for environmentally friendly energy cooperating on common challenges, is a new way of thinking.


Svein Eggen

CO_2 value chain

The transport paper we published involved the evaluation of more than 400,000 different CO_2 transport chains...

Jana P. Jacobsen and Simon Roussanaly
SINTEF Energy Research

Jana P. Jacobsen

Amy Brunsvold

Simon Roussanaly

Asbjørn Torvanger

FME CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

From idea to working tool

While other BIGCCS sub-projects concentrate on specific parts of the CCS chain such as capture, transport or storage, this one takes a full-chain perspective.

The overall objective is to develop CCS value chain assessment as a means of selecting the most cost-effective options for CCS and to evaluate additional parameters such as environmental impacts and risk assessment.

- This is a big issue to deal with, and the long-term perspective of BIGCCS will enable us to build our model with the time required to reach our ambitious goals, says Simon Roussanaly, who leads the task that focuses on CO_2 chain analysis, environmental impacts, and safety.

- Our methodology and models are important because it has often been difficult to draw conclusions regarding on the outcome of CCS, as several studies have reached opposing conclusions, probably because they have started from different hypotheses. For this reason, we are developing a consistent and transparent methodology and a tool for assessing the complete CCS chain.

Super-model

Roussanaly and his colleagues Jana Jakobsen, Amy Brunsvold and Erik Hognes are building a super-model for CCS, adopting various capture, transport and storage technologies as the basic structures.

- Using this model, we can assess the technical, economic and environmental characteristics of several possible CCS chains. This allows us for example, compare different technology options within the chain or illustrate how a chain, or part of a chain, is

affected by parameters such as capacity, cost and efficiency. Our model is also built in such a way that input information can be modified easily when better data become available, says Roussanaly.

In order to select the most cost-effective CCS chains and illustrate how costs of implementing CCS chains can be decreased, our models are built on advanced technical modelling of the different parts of the CCS chains.

- To build the technology part of our models, we often collaborate with the other sub-projects. For example, we have already been working closely with the group focusing on capture, and we are now working with the storage people to model CO_2 storage, especially when this is combined with enhanced oil recovery (EOR).

Presenting the model

To illustrate the hypotheses involved, and the advantages and potential of its methodology, Roussanaly's group is now presenting the model to partners, and is publishing several papers based on its application.

- For example, the transport paper that we published last year involved the evaluation of more than 400,000 different CO_2 transport chains to evaluate when pipelines or shipping should be used and to address the impact of complex issues on the selection of transport technology. This would have been impossible without a model like ours.

- Another case study that we performed illustrated how the cost of capturing CO_2 from a coal power plant, in which the CO_2 emissions fluctuate throughout the day and with the seasons, changes with the installed capture capacity. The results showed that not capturing at full capacity could lower capture costs by a factor of three.

By illustrating how technologies can be selected and chains can be designed to cut the costs of CCS, CCS will become a more cost-attractive means of eliminating CO_2 emissions to the atmosphere, and will therefore be implemented earlier.

Industry focus

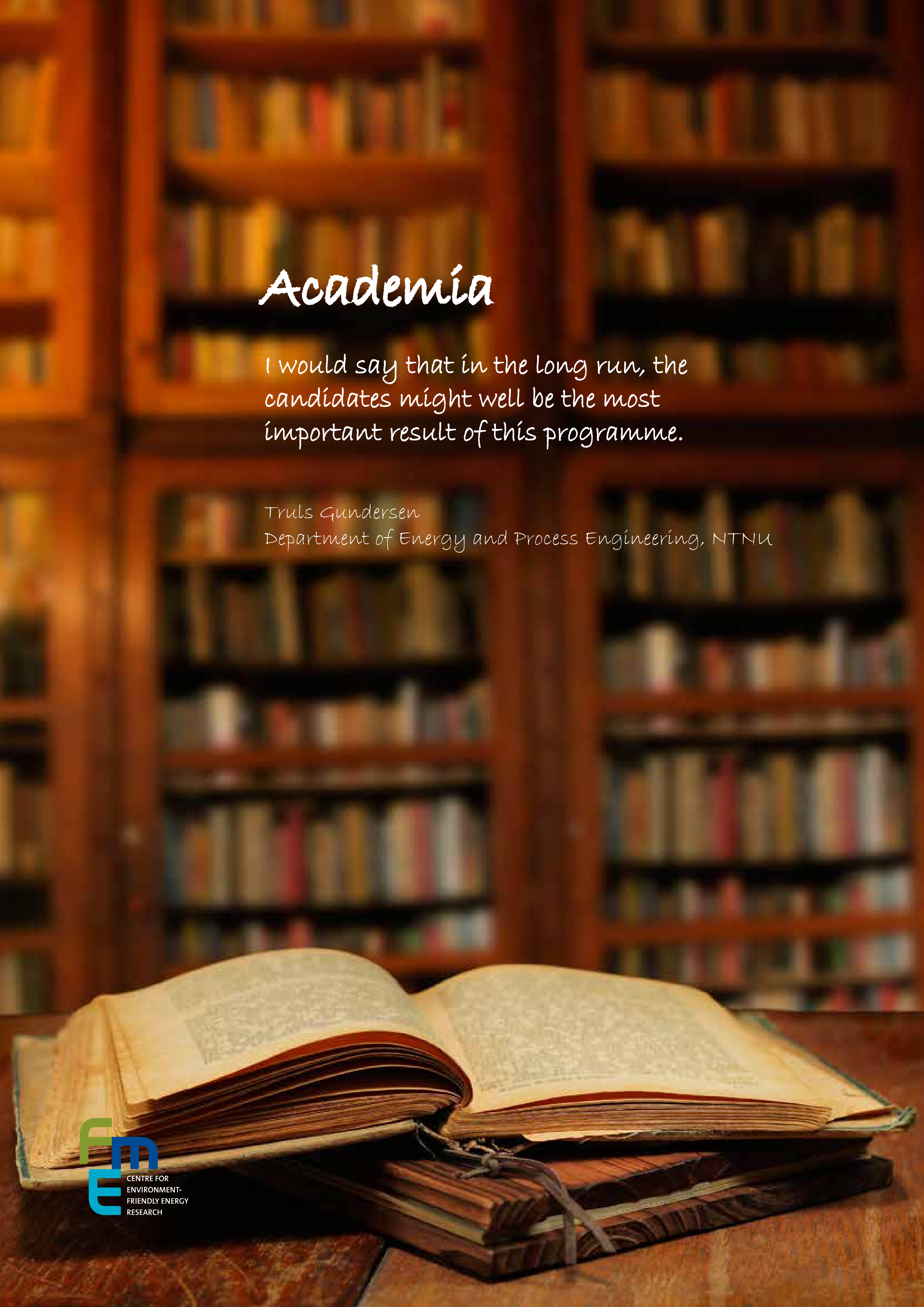
Simon Roussanaly is impressed by the interest shown by industry.

- It actually surprised me; some companies are quite active, asking questions, wanting to know how our model works and how they could use it. This year, we are going to present the model in detail to our industrial partners. They will be able to see that our models are based on advanced modeling techniques and consider how they could use them to assess their own case studies and to evaluate certain effects on the CCS chain.

Leader CO_2 value chain:
Amy Brunsvold
Research Scientist
SINTEF Energy Research

Achievements:

- Development of a consistent and transparent multi-criteria framework for assessing CCS chains.
- Development of modules to estimate the costs and climate impact of different links in the CCS chain (capture, transport and storage).
- Assessment of the impact of CO_2 concentration on an amine-based post-combustion CO_2 capture process by considering the technical, economic, and environmental assessments in conjunction.
- Systematic evaluations of pipeline and shipping transportation and quantifications of how important parameters impact decisions made in this area.
- Quantifications of the impact of CO_2 capture plant capacity on capture cost in the case of a coal-fired power plant with flexible profile to promote better capacity selection and better investment decisions.
- Economic evaluations of flexibility and associated plant operation parameters through the analysis of a base-load coal-fired power plant with flexible post-combustion CO_2 capture in a market with cyclical electricity price patterns.
- Modelling of a CO_2 emission mitigation market with CO_2 storage, uncertain leakage and learning.
- One Post-doc on value chain analysis has completed studies.
- 14 journal and conference papers published and 21 presentations at conferences.



Academia

I would say that in the long run, the candidates might well be the most important result of this programme.

Truls Gundersen
Department of Energy and Process Engineering, NTNU

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People and publications

A large volume of publications and a growing number of PhD students and Postdocs make the days busy for Truls Gundersen – head of the academia sub-program at BIGCCS.

The BIGCCS family is getting bigger every year in terms of PhD students and Postdocs, but they are all taken care of by the head of the "family"; Professor Truls Gundersen of the Department of Energy and Process Engineering at NTNU.

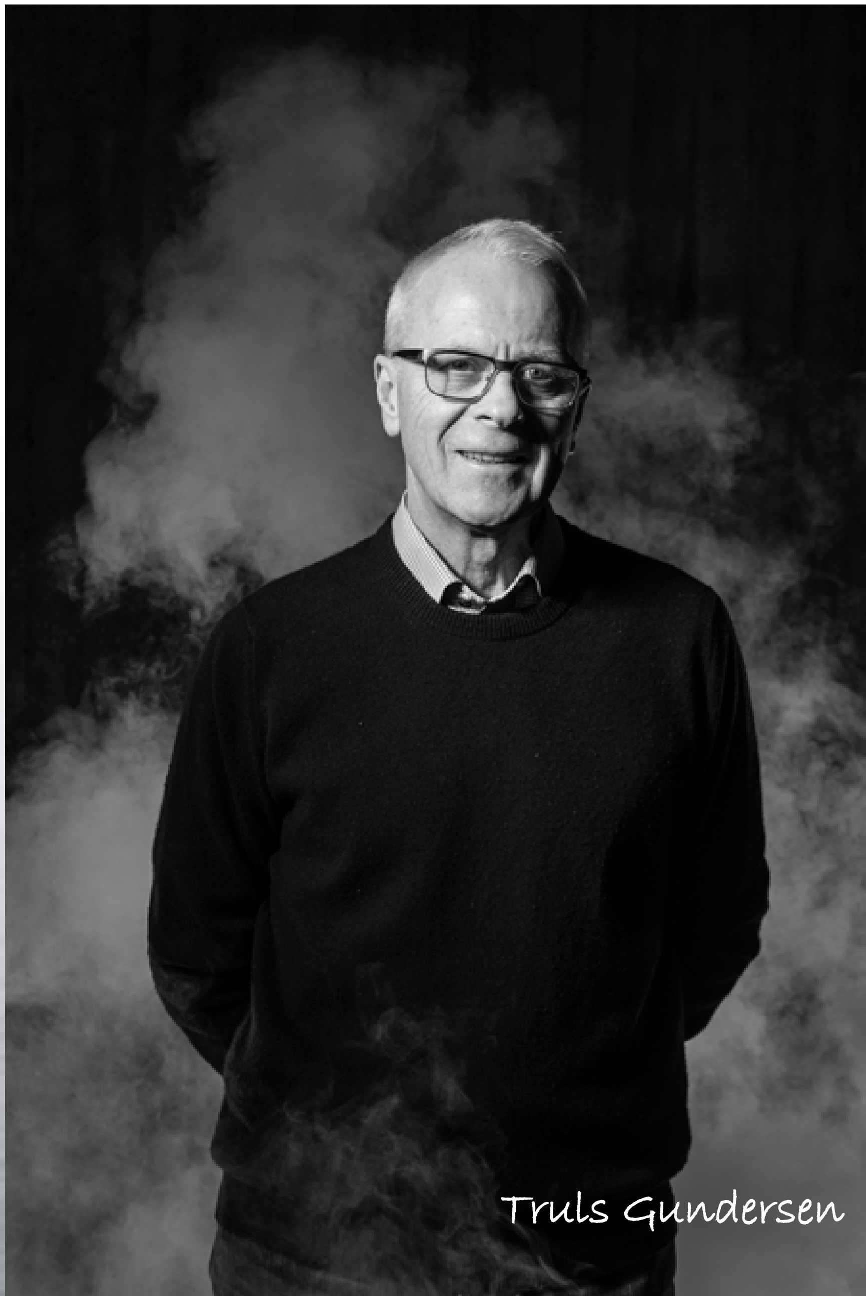
– We currently have 28 members of the "family", who come from 10 different countries all over the world. There are 22 PhD students and six Postdocs – some of them have already finished and have moved on, says Gundersen.

– The proportion of international PhD students at NTNU has increased considerably during the past few years, and it has also been difficult to recruit Norwegian female candidates to PhD research. BIGCCS has been a positive exception here, since six out of the 28 researchers are Norwegian, and eight of the PhD students are women, three of them from Norway.

Complex and interesting

– BIGCCS is one of the most complex projects I have ever worked on, with a wide range of disciplines, says Truls Gundersen, and he has been around.

He has an MSc in physics and a PhD in chemical engineering, plus 12 years industrial experience with Norsk Hydro. He has been Professor of Mechanical Engineering at NTNU since 1996.



– This is the first time my department has collaborated with people from SINTEF Petroleum Research. All the candidates have their project tasks within one of the sub-projects and are spread all over the university. One important challenge of BIGCCS is to make sure that the candidates feel that they have something in common.

To deal with this aspect, Gundersen has arranged several gatherings in 2013, at which the PhDs can meet to talk, discuss, and exchange experience. He has also organised PhD seminars at which they give lectures, and they also attend Consortium Days with the industrial partners.

– These give the students a chance to introduce themselves and build their network of contacts – after all there is a life after BIGCCS. We believe that CCS activity will also be increasing internationally.

International Cooperation

Truls Gundersen sees clearly the value of international cooperation and interdisciplinary working.

– In the early 1980s, the Research Centre of Norsk Hydro consisted mainly of chemical engineers. I experienced the great value of a more diversified staff when personnel with different backgrounds were recruited. I have been actively involved in NTNU's strategy for collaboration with excellent international universities such as MIT and Shanghai Jiao Tong University, and the value of these relationships is considerable in NTNU's efforts to become an internationally recognized university of excellence.

Truls Gundersen has also been supervising three candidates himself; one PhD student and two Postdocs. They are from China and India, two countries that are heavily dependent on coal.

– For me it is important to see how we can reduce emissions from countries like that, as this will count much more than anything that little Norway can do itself.

– I would say that in the long run, the candidates might well be the most important result of this programme. Of course, it is important to focus on the big goals – like saving the planet. But the research being done here is in many senses pioneering work. It is important to mention that the students are working within a large master's program, and in the future many of them will probably work on this and related issues in industrial companies or research institutes. I am impressed by what they have presented at our seminars.

Publications

Professor Gundersen is also keeping track of the project publications in which the students are involved. It is a steady flow.

– You could say that there is a good climate for publishing in BIGCCS. I try to keep track of the publications, of which the students have been co-authors and over the years this curve has gone up considerably. This is a good sign.

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Good recruitment

Last year BIGCCS and the CLIMIT programme held a joint PhD seminar at Lerkendal Stadium in Trondheim. The co-organizer was Aage Stangeland from the Research Council of Norway. After the seminar he said:

– The seminar showed that there are many clever PhD candidates financed by BIGCCS and the CLIMIT programme, and all are delivering very important and interesting results. For us it is important to make sure that we have good recruitment to the CCS field, and this can be done by financing PhD students and Postdocs for research centres and for single projects. It is important that all these young scientists meet and can learn from each other.

Aage Stangeland says that the idea behind such seminars is to make good synergies between BIGCCS and all the other centres and projects doing R&D within CCS. The value of this can be seen at different levels:

- The younger scientists expand their network
- By talking to other people than your daily colleagues the effect of learning is strengthened
- The impact of sharing knowledge between BIGCCS and other fields is much greater than without such seminars
- It is among young scientists that we may find the solutions for CO_2 capture, transport and storage

Aage Stangeland

Participants at the joint BIGCCS-CLIMIT PhD seminar.
Photo: Aage Stangeland

Speaking with...

Camilla Kaori Vigen

At the moment, Camilla is preparing to complete her PhD project. Still, she found time for sharing with us her experiences from her studies at the University of Oslo.

What issue within BIGCCS is addressed by your work?

My PhD project is part of the sub-programme Capture, Task 1.2: High-temperature membranes. My focus has been on dense ceramic membranes in pre-combustion CCS. The main objectives of my work have been to identify new materials for this application and to improve our fundamental understanding of hydrogen transport through dense ceramic membranes.

What has been most positive and challenging about being a PhD student?

The most positive aspect of being a PhD student is that I have the opportunity to do basic research and the freedom to dive into fundamental aspects of my topics. The biggest challenge is combining the development of the creativity that is needed to come up with new ideas with the critical thinking that is necessary for a sound scientific discussion. I have been lucky in having excellent supervisors to guide me.

What are your experiences of working in a centre with so many partners?

My closest contacts among the partners in BIGCCS have been SINTEF, through the Materials and Chemistry Group in Oslo, and NTNU, through the Inorganic Materials and Ceramic Research Group in Trondheim. We have had regular meetings, and the PhD students have been invited when SINTEF Materials and Chemistry has had visits from industrial partners. I have also met representatives of the other partners at workshops and consortium days. Working in a centre has given me the chance to learn more about the other aspects that are important in the whole CCS-chain and thereby obtain a better view of "the bigger picture".

How would you describe your collaboration with other scientists and industrial partners?

The collaborations I have been involved in have been very good. Collaboration within UiO is excellent, with good communication with my supervisors and fellow BIGCCS students. I have also felt welcome to collaborate with the scientists at SINTEF Materials and Chemistry, which is our most natural research partner, and we had a joint publication together with Statoil in 2012. Due to the nature of my PhD project, which is quite closely focused on basic research, further contact with industrial partners has

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- Working in a centre has given me the chance to learn more about the other aspects that are important in the whole CCS-chain and thereby obtain a better view of "the bigger picture".

Camilla Kaori Vigen
PhD student,
Department of Chemistry
University of Oslo

been limited to BIGCCS workshops and visits to SINTEF. Still, this has been a positive experience as it has given me better insight into how CCS is regarded from an industrial perspective.

Do you feel that this is an important issue to take part in?
Certainly! Since it is not likely that renewables will be capable of meeting the world`s energy consumption for many years yet, the development of CCS is a step in the right direction. Natural gas is still abundant and is likely to be an important energy source/ reactant in industrial processes for many years to come, and the technology that is being developed for CCS may also find other novel applications related to more energy-efficient and environmentally friendly utilisation of fossil fuels.

How is the ability to show your work during this period?
PhD- and Post Doc seminars are arranged through the Academia sub-program, where we are asked to give presentations on such a level that we can communicate to colleagues outside of our fields. This is a great opportunity to learn about other CCS-related research topics, and also for socialization with the other BIGCCS-students. We are also invited to give presentations in BIGCCS workshops, which give us the opportunity to discuss our work with each other as well as representatives for the

Speaking with...

Andy Chadwick

As a representative of the R&D partners, we have spoken with Dr. Andy Chadwick. He has been involved with CO_2 storage since 1998 and participated in many European CO_2 storage projects and a number of UK government and industrially-funded ones.

In what way is CCS important to you as a scientist, and what was your motivation for getting into this project?

My primary motivation is my concern about the dangers of global warming. As a geologist, two things are clear to me. First, the level and rate of current greenhouse gas emissions to the atmosphere is unprecedented on geological time-scales. Second, based on our understanding of previous mass extinction events, uncontrolled global warming could easily lead to the end of advanced life on our planet.

What do you see as the biggest challenges to CCS deployment?

I see the initial capital costs and the lack of credible and binding international emissions reduction agreements and legislation. Although over the full life-cycle CCS is very competitive with other low carbon technologies, major investment is required up-front to build a capture-transport-storage system. Without assurance of future investment security (in terms of carbon price, regulatory regimes, governments' energy policy, etc.), companies are very reluctant to risk the large amounts of capital required.

What have been the most important contributions from BIGCCS?

My involvement in BIGCCS is on the storage research side. Underground storage of CO_2 requires that we can safely contain hundreds of millions of tonnes of a buoyant, mobile fluid for a very long time - many thousands to millions of years. BIGCCS research has focussed on some of the key aspects of demonstrating storage viability. We have worked on storage capacity, showing that offshore reservoirs beneath the North Sea can safely store many decades of European CO_2 emissions.

Another key aspect is to show that storage sites stabilise with time. BIGCCS has performed theoretical studies using advanced mathematical tools, coupled with computer modelling of fluid flow, to show that CO_2 dissolves in aquifer water and fluid convection systems develop naturally which transport the CO_2 downwards in the storage reservoir. This is a very important stabilisation process, and we are now working on new laboratory experiments to further validate this theory.

We have also done a lot of work on the monitoring of storage sites – showing where the CO_2 gathering and how the site is performing. Much of this work is based on monitoring datasets provided by the

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Norwegian CO_2 storage sites at Sleipner in the North Sea and Snøhvit in the Barents Sea. Our work on time-lapse 3D seismics (a sophisticated echo-sounding technique) has shown that we can image CO_2 plumes with a high degree of accuracy, detecting layers of CO_2 as thin as a metre or less – at depths of a kilometre or more. We are also using computer models to simulate how the CO_2 accumulations are evolving with time, to show that we understand the processes operating at depth, and to give confidence in future predictions. Some of our recent work has focussed on the mechanical aspects of storage – showing how to ensure that reservoirs and caprock seals remain intact as pressure in the storage reservoir is increased.

What are the positive sides of being a partner in such a large undertaking/centre?

Our activities as part of the BIGCCS centre significantly enhance the international reputation of the British Geological Survey's CCS team as we get access to a wide range of innovative ideas from scientists with different skills and viewpoints. This has enabled us to develop new lines of research with a real multidisciplinary flavour, and it is really rewarding working with international experts helping to solve the obstacles that stand in the way of full-scale deployment of CO_2 storage projects. It is also the case that because BIGCCS covers the full chain of CCS, we also get to learn about the leading-edge research in capture and transport. This involves seeing research in completely different areas of science such as chemical and mechanical engineering and helps us to obtain a really good perspective on the whole CCS concept.

How would you describe the collaboration with your Norwegian colleagues?

The collaboration is very good. Being a geological survey, we have somewhat different expertise to SINTEF which is a specialised petroleum research institute, and NTNU which provides a wide range of capabilities in terms of mathematics and physics. Our skills and facilities therefore complement each other and we are able to develop research in ways that a single institution would find impossible. For example, we have a joint research paper between NTNU and BGS under review on discriminating between pressure and saturation effects on seismic data following CO_2 injection, and we were recently involved in a joint bid to the Norwegian CLIMIT call at the end of 2013. The bid was successful and is headed by the geophysics group at SINTEF Petroleum Research in Trondheim, with BGS providing geological and geophysical expertise. Erik Lindeberg, the chief scientist at SINTEF Petroleum Research, is one of the real pioneers in CO_2 storage research and it is always good to see Erik at the meetings and hear his latest ideas for new projects and experiments.

- The primary motivation is my concern about the dangers of global warming.

Dr Andy Chadwick
Team Leader
CO_2 Capture and Storage
British GeologicalSurvey,
Natural Environmental Research Council, UK

Speaking with...

May-Britt Hägg

Professor May-Britt Hägg is heading the membrane research group MEMFO at the Department of Chemical Engineering at NTNU. For around 20 years her focus has been on membranes for renewable energy and also carbon capture. She leads the Scientific Committee of BIGCCS, a role she finds very interesting and rewarding.

What have been BIGCCS's most important contributions so far?

The programme has managed to include alternative methods, for example for capture technology during its first period, including technologies which had not been thought of at the start. That is a good thing. There is also a focus on efficient combustion technology, which is energy-saving in itself.

All the paths are all very important, but scientists tend to stick to their own field and their own research. Some of the main tasks for the scientific committee are to maintain an overview, to make sure that we include new research areas and that things are seen in relation to each other in the big picture.

How do you judge the work that has been done so far in this project?

A lot of good work has already been done, and I am particularly keen on the academic part of the programme, with its PhD training and the publication scheme. The research is being documented through open published papers and is presented at international conferences. This is a very good way of getting a discussion going about the research and the process. Many PhD, and postdoc researchers are attached to the program, and they contribute to various work packages and are well taken care of. In some areas there have been difficulties in getting people to understand the importance of what has been done within a broader perspective. That is for the Scientific Committee to pinpoint – and to suggest where it should be possible to obtain new information. We have a well-documented process which is open to others, and that is very important.

Even though the EU does a lot of research on CCS, BIGCCS is different. The programme is a good opportunity to look at the whole value chain. I am sure that many scientists all over Europe would like to join if they had the chance.

Eight years is a long time for a project – In what way is this positive?

Yes, it is a long time, but this is also one of its advantages. Research takes time – it is a long way from the laboratory to a small-scale pilot and then on to full-scale testing. It is difficult and very expensive to do this. If we are going to succeed, good results from the laboratory will not be enough; we have to take every little step up to full-scale testing. And at this point in time, politicians in Europe seem to be reluctant to go the whole way. It will always be expensive to build the first project, and to perform the full-scale tests, but we must take this first important step.

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What do you regard as the biggest challenge to CCS deployment?

The biggest problem facing CCS deployment is the slow speed at which it is being brought forward to implementation. Basically it is a question of money – of not wanting to invest enough in research and piloting various technologies. I also believe that CCS research has ended up in unhealthy competition with renewable energy research – we desperately need both renewable energy and fossil fuels in the future.

The report from IEA (International Energy Agency), the World Energy Outlook 2012, points out how much fossil fuel we can extract before we reach the ″2 degree goal″. If we continue at the same speed as today without speeding up the development of CCS, we will only be able to produce a third of the available reserves of coal and gas. This is not an option today, given the rapid economic growth of previously third-world countries, and the increase in population.

In Europe today there are few major CCS programmes, and this is part of our problem. We need to communicate to politicians and the general public that we will be dependent on fossil fuels for a long time yet. Renewable energy is a part of the solution, but we cannot switch from one day to the next. The transition phase will take a long time.

- A lot of good work has already been done, and I am particularly keen on the academic part of the programme, with its PhD training and publication scheme.

May-Britt Hägg
Professor, Department of Chemical Engineering, NTNU
Chair of the BIGCCS Scientific Committee

Speaking with...

Tone Ibenholt and Åse Slagtern

Special Adviser Åse Slagtern is a staff member of the Natural Gas Power (CLIMIT) and has been working with BIGCCS from the start. Tone Ibenholt is responsible for Norway's Centres for Environment friendly Energy Research in the Norwegian Research Council.

What are the experiences with the FME scheme so far?

The main objective of the FME scheme is to establish research centres that perform concentrated, long-term research of high international quality in the area of environmentally friendly energy.

The achievements of the centres so far are generally very impressive. The midway evaluation showed that the FMEs have established clearly defined research profiles and engaged extremely competent scientists. Many of them are operating at a high international level. The long-term cooperation between research and industry in an FME is likely to provide a strong basis for innovation. As we see it, the FME scheme has improved the dialogue between industry and research partners and thus contributed to research that is highly relevant to industry. The scheme has also led to more research cooperation and to the establishment of strong research groups that cross institutional boundaries in Norway.

Where BIGCCS itself is concerned, the centre has definitely succeeded in building a strong international research group which is very well recognised.

What do you see as the biggest challenges to CCS deployment?

CCS has the potential to become one of the most important options for mitigating climate change – if we manage to solve the challenges the technology presents. One of the most important challenges is that there is currently no market for CCS. A commercial market for CO_2 is not expected until 2030; the main reasons being the international financial crisis, the lack of regulation and international climate agreements, and too low a price on CO_2 emissions. Public acceptance is also a challenge. It is essential that all these factors should operate in the same direction to stimulate industry to develop more effective technology for a future commercial market.

There is currently a need for a demonstration of CCS technology performed in close collaboration with research and development activities.

- CCS has the potential to become one of the most important options for mitigating climate change – if we manage to solve the challenges.

How important is it for Norway/ the Research Council of Norway to successful in this project?
The Research Council regards the FMEs as an important instrument for developing new environmentally friendly technology. The centres lay the ground for long-term research together with user partners. The centres are one of several instruments that collaborate with research programmes such as CLIMIT and ENERGIX, which are also important tools that enable the Research Council to build and develop strong research groups and ensure good collaboration between industry and research, although other mechanisms will also be required to upscale and commercialise the technologies.

In Norway, the full-scale CO_2 capture Mongstad project (CCM) was stopped, and it is very important to continue research and technology development in the field. Norway has put a great deal of time, effort and money into generating knowledge in this field. If we leave drop commitment, scientists will take on other assignments and the competence already developed will vanish. We must continue R & D and focus on smart solutions and the technology of the future. In this context, BIGCCS is of great importance.

Tone Ibenholt
Special Adviser
Division for Energy, Resources and the Environment
Research Council of Norway

Åse Slagtern
Special Adviser,
Division for Energy, Resources and the Environment
Research Council of Norway

Partners

Host Instituition:

SINTEF Energi AS / SINTEF Energy Research

Research Institutes:

- BGS - Natural Environment Research Council
- CICERO Center for International Climate and Environmental Research – Oslo
- Deutsche Zentrum für Luft- und Raumfahrt
- GEUS - Geological Survey of Denmark and Greenland
- Geological Survey of Norway (NGU)
- NTNU Social Research AS
- SINTEF Petroleum Research AS
- SINTEF Foundation

Universities:

- Norwegian University of Science and Technology (NTNU)
- University of Oslo (UiO)
- TU München by Lehrstul Für Thermodynamik

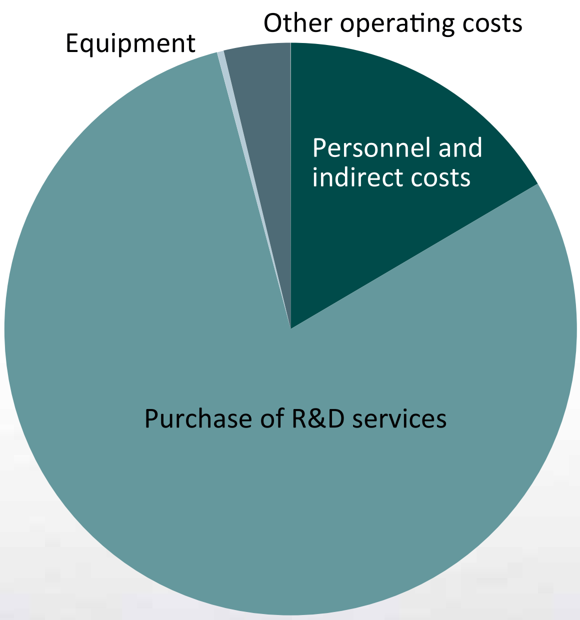
Industry:

- ConocoPhillips Skandinavia AS
- Gassco AS
- GDF Suez
- Shell Technology Norway AS
- Statoil
- TOTAL E&P Norge AS

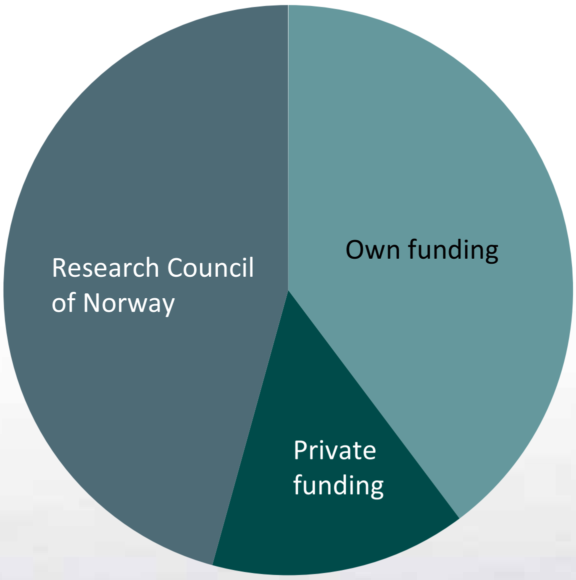
CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Key figures

Actual costs



Funding



Actual costs	**NOK**
Personnel and indirect costs	7 234 157
Purchase of R&D services	34 706 381
Equipment	160 781
Other operating costs	1 649 143
Total	**43 750 462**

Funding	**NOK**
Own funding	17 389 574
Private funding	6 360 888
Research Council of Norway	20 000 000
Total	**43 750 462**

Key Researchers

CO_2 Capture

Name	Affiliation	Degree	Sex	Position
Andrea Gruber	SINTEF Energy Research	PhD	M	Senior research scientist
Bjørnar Arstad	SINTEF Materials and chemistry	PhD	M	Research scientist
Geir Haugen	SINTEF Materials and chemistry	MSc	M	Research scientist
Hanne Kvamsdal	SINTEF Materials and chemistry	PhD	F	Senior 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
Karl Anders Hoff	SINTEF Materials and chemistry	PhD	M	Senior scientist
Kristin Jordal	SINTEF Energy Research	PhD	F	Research scientist
Marie-Laure Fontaine	SINTEF Materials and chemistry	PhD	F	Senior scientist
Mario Ditaranto	SINTEF Energy Research	PhD	M	Research manager
Nils Erland L. Haugen	SINTEF Energy Research	PhD	M	Research scientist
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
Truls Norby	UiO	PhD	M	Professor
Ugochukwu Edvin Aronu	SINTEF Materials and chemistry	PhD	M	Research scientist
Wen Xing	SINTEF Materials and chemistry	PhD	M	Research scientist
Yngve Larring	SINTEF Materials and chemistry	PhD	M	Senior scientist
Øyvind Langørgen	SINTEF Energy Research	PhD	M	Research scientist

CO_2 Transport

Name	Affiliation	Degree	Sex	Position
H. G. Jacob Stang	SINTEF Energy Research	Dr.ing	M	Research scientist
Håkon Ottar Nordhagen	SINTEF Materials and chemistry	PhD	M	Research scientist
Morten Hammer	SINTEF Energy Research	PhD	M	Research scientist
Ingrid Snustad	SINTEF Energy Research	MSC	F	Research scientist
Sigmund Ø. Størset	SINTEF Energy Research	MSc	M	Research manager
Sigurd W. Løvseth	SINTEF Energy Research	Dr.ing.	M	Research manager
Svend T Munkejord	SINTEF Energy Research	PhD	M	Chief scientist

CO_2 Storage

Name	Affiliation	Degree	Sex	Position
Alexandre Lavrov	SINTEF Petroleum Research	PhD	M	Senior scientist
Alv-Arne Grimstad	SINTEF Petroleum Research	PhD	M	Research manager
Andy Chadwick	BGS	PhD	M	Team leader CCS
Anna Stroisz	SINTEF Petroleum Research	PhD	F	Research scientist
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
Etor Querendez	SINTEF Petroleum Research	MSc	M	Research scientist
Gareth Williams	BGS	PhD	M	Geophysicist
Grethe Tangen	SINTEF Petroleum Research	PhD	F	Senior scientist
Idar Akervoll	SINTEF Petroleum Research	MSc	M	Senior scientist
James White	BGS	PhD	M	Geophysicist

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Name	Affiliation	Degree	Sex	Position
Jan Åge Stensen	SINTEF Petroleum Research	PhD	M	Senior research scientist
Jelena Todorovic	SINTEF Petroleum Research	PhD	F	Research scientist
John Williams	BGS	BSc	M	Geoscientist
Karen Lyng Anthonsen	GEUS	MSc	F	Geo-engineer
Lars Erik Walle	SINTEF Petroleum Research	PhD	M	Research scientist
Malin Torsæter	SINTEF Petroleum Research	PhD	F	Research scientist
Peder Eliasson	SINTEF Petroleum Research	PhD	M	Research manager
Peter Frykman	GEUS	PhD	M	Senior researcher
Pierre Cerasi	SINTEF Petroleum Research	PhD	M	Senior scientist
Raheleh Farokhpoor	NTNU	PhD	F	Post doc
Rasmus Rasmussen	GEUS	PhD	M	Senior advisor
Rob Cuss	BGS	PhD	M	Specialists
Robert Drysdale	SINTEF Petroleum Research	PhD	M	Senior adviser
Zhijun Du	SINTEF Petroleum Research	PhD	M	Senior scientist

CO_2 Value Chain

Name	Affiliation	Degree	Sex	Position
Amy Brunsvold	SINTEF Energy Research	PhD	F	Research scientist
Jana P. Jakobsen	SINTEF Energy Research	PhD	F	Senior research scientist
Erik Skontorp Hognes	SINTEF Fisheries and Aquaculture	MSc	M	Research scientist
Simon Roussanaly	SINTEF Energy Research	MSc	M	Research scientist

Academia

Name	Affiliation	Degree	Sex	Position
Børge Arntsen	NTNU	PhD	M	Professor
Christian Thaulow	NTNU	PhD	M	Professor
Hugo A. Jacobsen	NTNU	PhD	M	Professor
Inge R. Gran	NTNU	PhD	M	Adjunct Professor
Ivar Ståle Ertesvåg	NTNU	PhD	M	Professor
Jens P. Andreassen	NTNU	PhD	M	Professor
Jens-Petter Andreassen	NTNU	PhD	M	Assistant Professor
Jon Kleppe	NTNU	PhD	M	Professor
Jyh-Yuan Chen	UCB	PhD	M	Professor
Magne Hillestad	NTNU	PhD	M	Professor
Martin Landrø	NTNU	PhD	M	Professor
May-Britt Hägg	NTNU	PhD	F	Professor
Olav Bolland	NTNU	PhD	M	Professor
Ole Torsæter	NTNU	PhD	M	Professor
Reidar Haugsrud	UiO	PhD	M	Assistant Professor
Robert W. Dibble	UCB	PhD	M	Professor
Roland Span	RUB	Dr.ing.	M	Professor
Rune Holt	NTNU	PhD	M	Professor
Terese Løvås	NTNU	PhD	F	Professor
Thomas Sattelmayer	Tech. Univ. München	Dr.ing.	M	Professor
Tor Grande	NTNU	PhD	M	Professor
Truls Gundersen	NTNU	PhD	M	Professor

Acronyms:

BGS
Natural Environment Research Council

CICERO
Center for International Climate and Environmental Research – Oslo

DLR
German Aerospace Center

GEUS
Geological Survey of Denmark and Greenland

NGU
Geological Survey of Norway

NTNU
Norwegian University of Science and Technology

RCN
Research Council of Norway

RUB
Ruhr-Universität Bochum

TUM
Technische Universität München

UCB
Berkeley - University of California

UiO
University of Oslo

PhDs

	Start	Completed	Supervisor

Alexandre Morin, France | September 2009 | November 2012 | Inge R. Gran, NTNU
Thesis: Mathematical modelling and numerical simulation of two-phase multi-component flows of CO_2 mixtures in pipes
Currently employed: SINTEF Energy Research, Trondheim

Camilla K. Vigen, Norway | October 2009 | April 2014 | Reidar Haugsrud, UiO
Thesis: Novel mixed Proton Electron Conductors for Hydrogen Gas Separation Membranes
Currently employed: Protia AS, Oslo

Andrew North, USA | January 2010 | December, 2013 | Robert W. Dibble, UCB
Thesis: Experimental Investigations of Partially Premixed Hydrogen Combustion in Gas Turbine Environments
Currently employed: Gas Turbine Division, Siemens, Orlando, Florida

Don Frederick, USA | January 2010 | December, 2013 | Jyh-Yuan Chen, UCB
Thesis: Numerical Investigations of a Hydrogen Jet Flame in a Vitiated Coflow
Currently employed: Nevada Automotive Test Center (R&D)

Georg Baumgartner, Germany | February 2010, | September 2014 | Thomas Sattelmayer, TUM
Thesis: Experimental Investigation of Hydrogen Flashback Behavior in Turbulent Boundary Layers

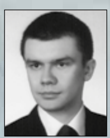
Rafael Antonio Sánchez, Argentina | March 2010 | Fall, 2014 | Hugo Atle Jakobsen, NTNU
Thesis: Modeling and Simulation of Sorption-enhanced Steam Methane Reforming (SE-SMR) operated in circulating Fluidized Bed Reactors

Vajiheh Nafisi, Iran | June 2010 | February, 2014 | May-Britt Hägg, NTNU
Thesis: Development of Mixed Matrix Membranes for Carbon Dioxide Capture
Currently employed: NTNU, Dept. of Chemical Engineering (Post.doc)

Amir Taheri, Iran | August 2010, | 2014 | Ole Torsæter, NTNU
Thesis: Study of Density-Driven-Natural-Convection (DDNC) Mechanism in CO_2 Sequestration in Heterogeneous and Anisotropic Brine Aquifer

Xinzhi Chen, China | August 2010 | December, 2013 | Tor Grande, NTNU
Thesis: Dense Oxygen Separation Membrane Materials – Thermal and Chemical Expansion of $La_{1-x}Sr_xMO_{3-\delta}$ (M = Fe, Co) and Tape Casting and Mechanical Properties of $La_2NiO_{4+\delta}$
Currently employed: NTNU, Dept. of Materials Science and Engineering (Post.doc)

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

	Name	Start	Completed	Supervisor
	**Sissel Grude, Norway** Thesis: Geophysical Monitoring of CO_2 Storage in the Subsurface Currently employed: Statoil (from 18 August 2014)	September 2010	Fall 2014	Martin Landrø, NTNU
	**Einar Vøllestad, Norway** Thesis: Mixed Proton Electron Conducting Oxides as Hydrogen Transport Membranes in Electrochemical Potential Gradients Currently employed: University of Oslo (Post.doc)	September 2010	February, 2014	Reidar Haugsrud, UiO
	**Xiaoguang Ma, China** Thesis: Precipitation in Carbon Dioxide Capture Processes Currently employed: NTNU, Department of Chemical Engineering (post.doc)	September 2010	April, 2014	Jens-Petter Andreassen, NTNU
	**Mansour Soroush, Iran** Thesis: Simulation and Experimental Investigation of Different Phenomena in CO_2 Storage in the Saline Aquifers Currently employed: Statoil	October 2010	No date yet	Jon Kleppe, NTNU
	**Robin Wegge, Germany** Thesis: Speed of sound and density measurements of binary, CO_2-rich mixtures over a wide temperature and pressure range.	October 2010	No date yet	Roland Span, RUB
	**Nina Enaasen, Norway** Research Topic: CO_2 Separation	January 2011	No date yet	Magne Hillestad, NTNU
	**Rengarajan Soundararajan, India** Thesis: Coal based Power Plants using Oxy-combustion for CO_2 Capture: Process Integration Approach to reduce Capture Penalty	August 2011	Fall, 2014	Truls Gundersen, NTNU
	**Espen Birger Raknes, Norway** Thesis: 3D elastic time-lapse full waveform inversion	September 2011	No date yet	Børge Arntsen, NTNU
	**Marcin Dutka, Poland** Thesis: Studies of Low NO_x Burner Technology	September 2012	No date yet	Terese Løvås, NTNU

	Name	Start	Completed	Supervisor
	**David Szewczyk, Poland**	December 2012	No date yet	Rune Holt, NTNU

Thesis: Rock physics and geomechanical aspects of seismic monitoring of CO_2 storage in the subsurface

Snorre Foss Westman, Norway | January 2013 | No date yet | Ivar Ståle Ertesvåg, NTNU

Thesis: Experimental investigation of phase equilibria of CO_2 mixtures relevant for CCS

Sohrab Gheibi, Iran | May 2013 | No date yet | Rune Holt NTNU

Thesis: Geomechanical Modelling of CO_2 Injection and Storage

Vera Hoferichter, Germany | May 2013 | No date yet | Thomas Sattelmayer, TUM

Thesis: Experimental Investigations on the Influence of Acoustic Excitations on Flame Flashback during Premixed Hydrogen Combustion in a Model Burner

Post.doc

Anwar Bhuiyan, Bangladesh | April 2010 | August 2011 | Martin Landrø, NTNU

Research Topic: Monitoring, Leakage and Remediation

Currently employed: Petroleum Geo-Services (PGS)

Hassan Karimaie, Iran | July 2010 | April 2012 | Ole Torsæter, NTNU

Research Topic: Storage Behavior

Currently employed: Aker Solutions

Xiangping Zhang, China | April 2011 | March 2013 | Truls Gundersen, NTNU

Research Topic: CO_2 Value Chain

Currently employed: Chinese Academy of Science, Beijing

Nousha Kheradmand, Iran | August 2012 | August, 2013 | Christian Thaulow, NTNU

Research Topic: CO_2 Pipeline Integrity

Currently employed: NTNU, Department of Engineering Design and Materials

Chao Fu, China | September 2012 | No date yet | Truls Gundersen, NTNU

Research Topic: Integrated Assessment and Oxy-Combustion

Raheleh Farokhpoor, Iran | December 2012 | No date yet | Ole Torsæter, NTNU

Research Topic: Effects of CO_2 on Rock Properties

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

Publications

Anantharaman, Rahul; Berstad, David Olsson; Jordal, Kristin. ***Process design of post-combustion CO_2 capture from a natural gas combined capture using Ca-looping process.*** 2[nd] Post Combustion Capture Conference; 2013-09-17 - 2013-09-20

Anantharaman, Rahul; Berstad, David Olsson; Jordal, Kristin; Gundersen, Truls. ***The role of Process Synthesis in the systematic design of energy efficient fossil fuel power plant with CO_2 capture.*** 16[th] Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES13); 2013-09-29 - 2013-10-03

Anantharaman, Rahul; Jordal, Kristin; Berstad, David Olsson; Gundersen, Truls. ***The role of process synthesis in the systematic design of energy efficient fossil fuel power plants with CO_2 capture.*** Chemical Engineering Transactions 2013; Volum 35. p. 55-60

Anantharaman, Rahul; Jordal, Kristin; Gundersen, Truls. ***CO_2 Capture Processes: Novel Approach to Benchmarking and Evaluation of Improvement Potentials.*** Energy Procedia 2013; Volum 37. p. 2536-2543

Anantharaman, Rahul; McCann, Michael; Peters, Thijs; Fontaine, Marie-Laure; Henriksen, Partow Pakdel; Mejdell, Thor. ***Process design and analysis of dual-phase membranes for off-shore post-combustion capture from gas turbines.*** 7[th] Trondheim Conference on CO_2 Capture, Transport and Storage (TCCS-7); 2013-06-04 - 2013-06-06

Anantharaman, Rahul; Roussanaly, Simon; Westman, Snorre Foss; Husebye, Jo. ***Selection of Optimal CO_2 Capture Plant Capacity for Better Investment Decisions.*** Energy Procedia 2013; Volum 37. p. 7039-7045

Arstad, Bjørnar; Spjelkavik, Aud I.; Andreassen, Kari Anne; Lind, Anna Maria; Prostak, Joanna; Blom, Richard. ***Studies of Ca-based high temperature sorbents for CO_2 capture.*** Energy Procedia 2013; Volum 37. p. 9-15

Aursand, Eskil; Aursand, Peder; Berstad, Torodd; Dørum, Cato; Hammer, Morten; Munkejord, Svend Tollak; Nordhagen, Håkon Ottar. ***CO_2 pipeline integrity: A coupled fluid-structure model using a reference equation of state for CO_2.*** Energy Procedia 2013; Volum 37. p. 3113-3122

Aursand, Eskil; Dørum, Cato; Hammer, Morten; Morin, Alexandre; Munkejord, Svend Tollak; Nordhagen, Håkon Ottar. ***CO_2 pipeline integrity: Comparison of a coupled fluid-structure model and uncoupled two-curve methods.*** The 7[th] Trondheim CCS Conference; 2013-06-04 - 2013-06-06

Berstad, David Olsson; Anantharaman, Rahul; Nekså, Petter. ***Integrated Low-temperature CO_2 Capture from IGCC Power Plant by Partial Condensation and Separation of Syngas.*** Chemical Engineering Transactions 2013 p. 355-360

Berstad, David Olsson; Anantharaman, Rahul; Nekså, Petter. ***Integrated low-temperature CO_2 capture from IGCC power plant by partial condensation and separation of syngas.*** 16[th] Conference Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction (PRES13); 2013-09-29 - 2013-10-02

Berstad, David Olsson; Anantharaman, Rahul; Nekså, Petter. ***Low-temperature CCS from an IGCC Power Plant and Comparison with Physical Solvents.*** Energy Procedia 2013; Volum 37. p. 2204-2211

Berstad, David Olsson; Anantharaman, Rahul; Nekså, Petter. ***Low-temperature CO_2 capture technologies - Applications and potential.*** International journal of refrigeration 2013; Volum 36.(5) p. 1403-1416

Bischi, Aldo; Langørgen, Øyvind; Bolland, Olav. ***Double loop circulating fluidized bed reactor system for two reaction processes, based on pneumatically controlled divided loop-seals and bottom extraction/lift.*** Powder Technology 2013; Volum 246. p. 51-62

Blom, Richard; Håkonsen, Silje Fosse; Grande, Carlos Adolfo. ***Rotating bed reactor for CLC: Bed characteristics dependencies on internal gas mixing.*** Applied Energy 2013; Volum 113. p. 1952-1957

Ditaranto, Mario; Anantharaman, Rahul; Weydahl, Torleif. ***Performance and NO_x Emissions of Refinery Fired Heaters Retrofitted to Hydrogen Combustion.*** Energy Procedia 2013; Volum 37. p. 7214-7220

Ditaranto, Mario; Meraner, Christoph; Haugen, Nils Erland Leinebø; Saanum, Inge. ***Influence of long pulse duration on time-resolved laser-induced incandescence.*** Applied physics. B, Lasers and optics (Print) 2013; Volum 112.(3) p. 359-367

Dutka, Marcin Damian; Skarbø, Kjartan; Ditaranto, Mario; Løvås, Terese. ***Emission Characteristics of Hydrogen-Enriched Methane Fuelled Partially Premixed Bluff Body Burner.*** 6[th] European Combustion Meeting; 2013-06-26 - 2013-06-28

Publications

Farokhpoor, Raheleh; Akervoll, Idar Ragnvald; Torsæter, Ole. ***CO_2 capillary entry pressure into flow barrier and caprock.*** 7th Trondheim conference on CO_2 capture, transport and storage - TCCS-7; 2013-06-04 - 2013-06-06

Farokhpoor, Raheleh; Akervoll, Idar Ragnvald; Torsæter, Ole; Bjørkvik, Bård Johan Arnt. ***CO_2 capillary entry pressure into flow barrier and caprock.*** International Symposium of the Society of Core Analysts; 2013-09-16 - 2013-09-19

Fontaine, Marie-Laure. ***Les Céramiques Industrielles.*** I: Les Céramiques Industrielles. Dunod Editeur 2013 ISBN 978-2-10-057739-2. p. 333-367

Fu, Chao; Anantharaman, Rahul; Jordal, Kristin; Gundersen, Truls. ***Thermal efficiency for coal to power: from theoretical to practical assessments.*** ECOS'2013; 2013-07-16 - 2013-07-19

Fu, Chao; Gundersen, Truls. ***Optimal Integration of Compression heat within Oxy-Combustion Coal based Power Plants.*** AIChE 2013 Annual Meeting; 2013-11-03 - 2013-11-08

Fu, Chao; Gundersen, Truls. ***Process Integration for Energy Efficiency in Coal-based Power Plants with Carbon Capture.*** AIChE2013 Spring Meeting; 2013-04-28 - 2013-05-02

Fu, Chao; Gundersen, Truls. ***Process Integration in Oxy-Coal Combustion Power Plants.*** 3rd Oxyfuel Combustion Conference; 2013-09-09 - 2013-09-13

Fu, Chao; Gundersen, Truls. ***Recuperative Vapor Recompression Heat Pumps for Cryogenic Air Separation.*** International Process Integration Jubilee Conference 2013; 2013-03-18 - 2013-03-20

Fu, Chao; Gundersen, Truls. ***Recuperative Vapor Recompression Heat Pumps for O_2 supply.*** 3rd Oxyfuel Combustion Conference; 2013-09-09 - 2013-09-13

Garcia, Jorge H. ***Carbon capture and storage and geological leakage.*** Annual conference; 2013-06-26 - 2013-06-29

Garcia, Jorge H. ***Carbon capture and storage and geological leakage.*** Bergen Economics of Energy and Environment Research Conference; 2013-05-13 - 2013-05-14

Garcia-Lopez, Jorge Hernan. ***Risk of leakage from CO_2 storage sites: Implications for pricing of carbon capture and storage.*** The 7th Trondheim Conference on CO_2 capture, transport and storage; 2013-06-04 - 2013-06-06

Grude, Sissel; Dvorkin, Jack; Clark, anthony; Vanorio, Tiziana; Landrø, Martin. ***Pressure effects caused by CO_2 injection in the Snøhvit Field.*** First Break 2013; Volum 31.(12) p. 99-101

Grude, Sissel; Dvorkin, Jack; clark, anthony; Vanorio, Tiziana; Landrø, Martin. ***Pressure effects caused by CO_2 injection in the Snøhvit field.*** The Second Sustainable Earth Sciences (SES) Conference and Exhibition.; 2013-09-30 - 2013-10-04

Grude, Sissel; Landrø, Martin; Dvorkin, Jack. ***Rock physics estimation of cement type and impact on the permeability for the Snøhvit Field, the Barents Sea.*** Society of Exploration Geophysicists. Expanded Abstracts with Biographies 2013 p. 2670-2674

Grude, Sissel; Landrø, Martin; Osdal, Bård. ***Time-lapse pressure-saturation discrimination for CO_2 storage at the Snøhvit field.*** International Journal of Greenhouse Gas Control 2013; Volum 19. p. 369-378

Grude, Sissel; Osdal, Bård; Landrø, Martin. ***Sea-bed diffractions and their impact on 4D seismic data.*** Geophysical Prospecting 2013; Volum 61. p. 199-214

Hammer, Morten; Ervik, Åsmund; Munkejord, Svend Tollak. ***Method using a density-energy state function with a reference equation of state for fluid-dynamics simulation of vapor-liquid-solid carbon dioxide.*** Industrial & Engineering Chemistry Research 2013; Volum 52.(29) p. 9965-9978

Haugen, Nils Erland Leinebø; Tilghman, Matthew B.; Mitchell, Reginald E. ***The conversion mode of a porous carbon particle during oxidation and gasification.*** Combustion and Flame 2013; Volum 161.(2) p. 612-619

Håkonsen, Silje Fosse; Grande, Carlos Adolfo; Blom, Richard. ***Rotating bed reactor for CLC; effect of radial walls in the oxygen carrier bed and coke formation on separation efficiency.*** the 7th Trondheim CCS Conference; 2013-06-04 - 2013-06-06

Jakobsen, Jana Poplsteinova; Roussanaly, Simon; Mølnvik, Mona J.; Tangen, Grethe. ***A standardized Approach to Multi-criteria Assessment of CCS Chains***. Energy Procedia 2013; Volum 37. p. 2765-2774

Jordal, Kristin; Anantharaman, Rahul. ***Production and use of hydrogen in a CCS context.*** TCCS-7; 2013-06-05 - 2013-06-06

CENTRE FOR
ENVIRONMENT-
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RESEARCH

Publications

Jordal, Kristin; Anantharaman, Rahul; Genrup, Magnus; Aarhaug, Thor Anders; Bakken, Jørn; Lilliestråle, Astrid; Mejdell, Thor; Holt, Nancy J. ***Feeding a gas turbine with aluminum plant exhaust for increased CO_2 concentration in capture plant.*** TCCS-7; 2013-06-05 - 2013-06-06

Jordal, Kristin; Anantharaman, Rahul; Gruber, Andrea; Peters, Thijs; Henriksen, Partow Pakdel; Berstad, David Olsson; Bredesen, Rune. ***Novel gas turbine burner concept for IGCC: Integrated H_2 membrane for distributed feeding of hydrogen to the combustion air.*** TCCS-7; 2013-06-05 - 2013-06-06

Jordal, Kristin; Anantharaman, Rahul; Langørgen, Øyvind. ***Novel oxy-combustion gas turbine concepts for off-shore applications.*** 3rd Oxyfuel Combustion Conference (OCC3); 2013-09-09 - 2013-09-13

Langørgen, Øyvind; Saanum, Inge; Bakken, Jørn; Gardå, Odin Hoff; Morin, Jean-Xavier. ***Engineering approach for construction, process control and initial testing of a 150 kW_{th} chemical looping combustion reactor system.*** The 7th Trondheim CCS Conference (TCCS-7); 2013-06-04 - 2013-06-06

Langørgen, Øyvind; Saanum, Inge; Larring, Yngve; Blom, Richard; Mokkelbost, Tommy. ***Climit project 189984. BIGCLC Phase II. Large-Scale Demonstration of pressurized Chemical Looping Technology (CLC) in Natural Gas Power Generation with CO_2 Capture.*** Climit-dagene 2013; 2013-02-25 - 2013-02-26

Lavrov, Alexandre; Cerasi, Pierre. ***Numerical modeling of tensile thermal stresses in rock around a cased well caused by injection of a cold fluid.*** I: 47th US Rock Mechanics/Geomechanics Symposium Proceedings. American Rock Mechanics Association (ARMA) 2013 ISBN 978-0-9894844-0-4.

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Task descriptions

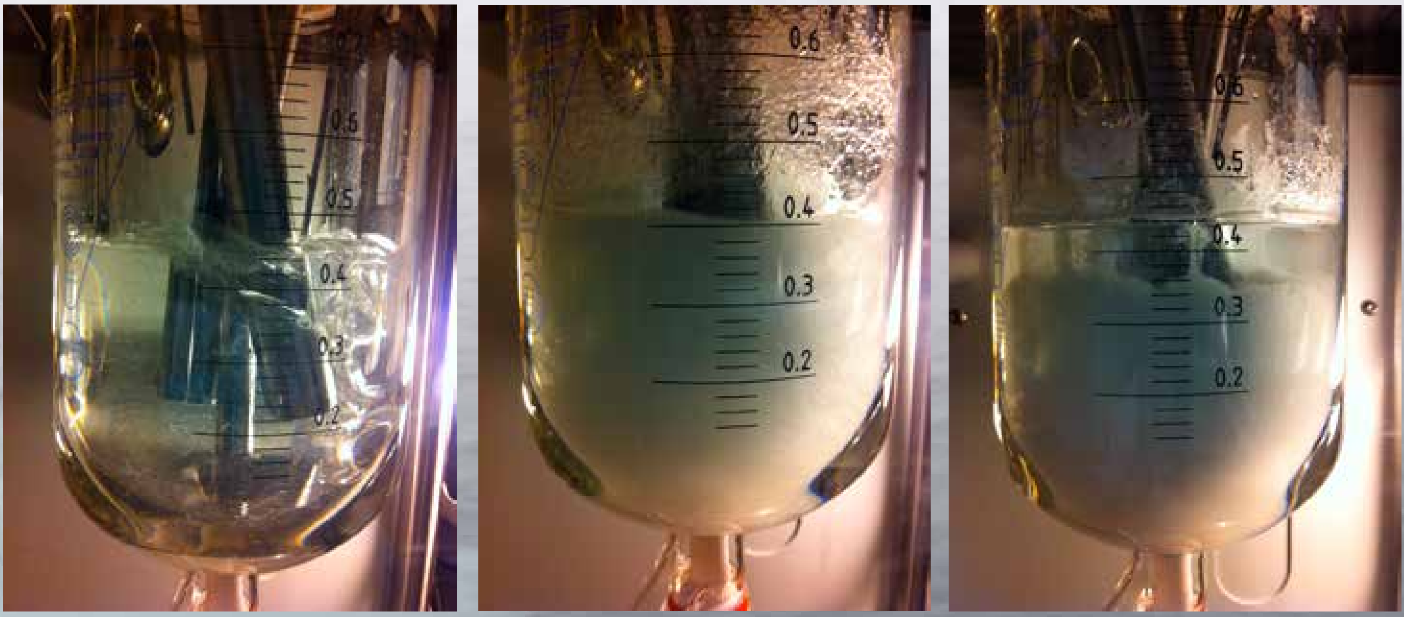
CO_2 Separation (1.1)

Work Package ”Absorption and absorption systems” consists of two main subtasks, Precipitating systems for CO_2 capture and Dynamic modeling and analysis of absorption based systems.

The impact of precipitation at process condition on energy number of an amino acid salt system has been evaluated by a short-cut method. The evaluation applied the developed vapor-liquid-solid equilibrium model, measured heat of reaction and physical property data of the precipitating system. The model shows that precipitation results in significant reduction in energy number. For dynamic modeling and analysis of absorption-based systems the dynamic process unit models have been improved and some work related to Model Predictive Control started. A dynamic test campaign has also commenced in the lab pilot.

In the Work Package ”High temperature sorbents for CO_2 capture” detailed X-ray studies of working sorbents, both pure dolomite and modified ones, have been performed.

We have been able to observe the effects of steam on the performance and further detailed studies have been undertaken and will be written up as a publication in 2014. We have further optimized the modification routes for the dolomites in order to improve cyclic stability. Operating cyclic sorption-desorption conditions have been studied and by using less fractions of the total sorbent capacity, stable cyclic capacity could be obtained for >100 cycles. The work in cooperation with Task 1.6 on the stability and cyclic capacity needed to make post-combustion carbonate looping feasible resulted in a work to be published in 2014.



Pictorial illustration of precipitation at process condition upon CO_2 absorption

High Temperature membranes (1.2)

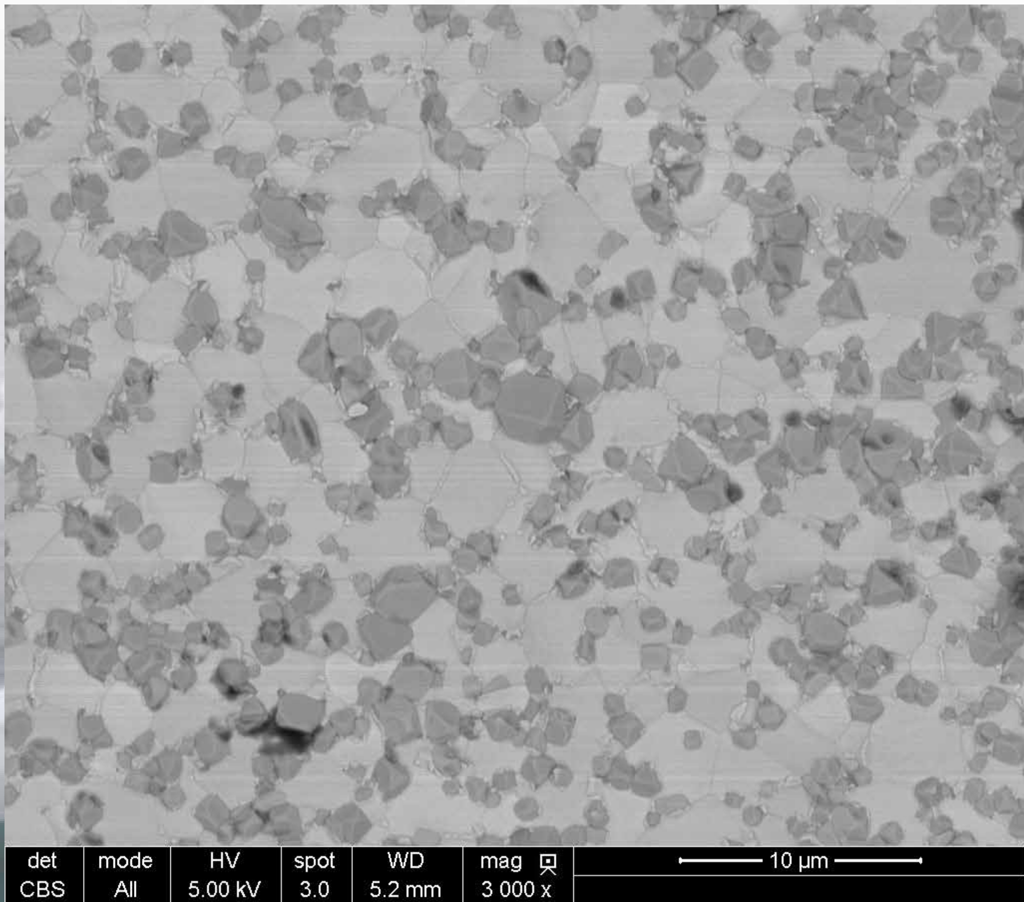
The work has focused on Hydrogen Transport Membranes (HTM) for pre-combustion CO_2 capture from high temperature processes such as steam methane reforming.

The H_2 permeability of novel ceramic composites of two mixed ionic-electronic conductors was investigated and found to be higher than the individual components. The figure shows a SEM micrograph of the surface of the produced membrane where the two phases are well mixed.

Furthermore, the H_2 permeability was similar to state-of-the-art ceramic membrane materials and ceramic composites were as such demonstrated as a promising strategy for improved HTM materials.

Investigation of hybrid membranes for post-combustion CO_2 capture hybrid membranes based on polymers with multifunctional nano-sized particles was initiated in collaboration with NTNU through a spin-off project (HyMemCOPI, KPN). Membranes produced at NTNU have been characterized at SINTEF and initial gas permeation experiments have begun.

Scanning electron microscope (SEM) micrograph of a ceramic composite of two mixed ionic-electronic conductors



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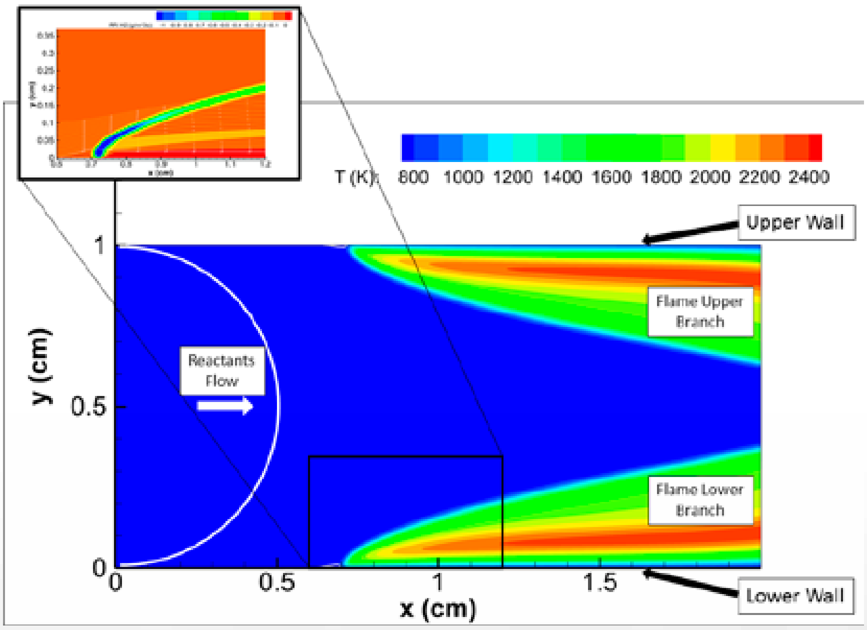
Hydrogen Combustion (1.3)

In 2013 the research effort within BIGCCS / Task 1.3 focused on the detailed characterization of laminar flames' behavior in connection with a novel distributed hydrogen fuel injection methodology through porous material.

Previous work has revealed the considerable challenges related to point sources (as in conventional fuel injection nozzles) of highly reactive fuels like hydrogen, therefore an alternative distributed fuel injection method based on porous diffusers, with or without a selective membrane layer, has been investigated.

Results indicate the occurrence of flashback, that is upstream flame propagation against the main flow of the reactants in the duct, even at relatively fuel-lean conditions and high reactants flow velocity whenever fuel is added through the porous wall. Conversely, flashback is not occurring for the case of solid walls.

Importantly, these results suggest that, in order to avoid flashback, great care should be taken in flow design within mixing duct that utilizes the new distributed fuel injection methodology.



Direct Numerical Simulation of H_2-air flame flashback in a duct with fuel-lean reactants entering on the left hand-side and additional fuel injection from porous walls: temperature contours indicate the presence of a highly stratified flame. Detail shows the hydrogen fuel reaction rate presence, locally, of a triple flame.

Oxy-fuel Combustion and Flue Gas Recirculation (1.4)

New improved optically accessible oxy-fuel combustor of the HIPROX facility.

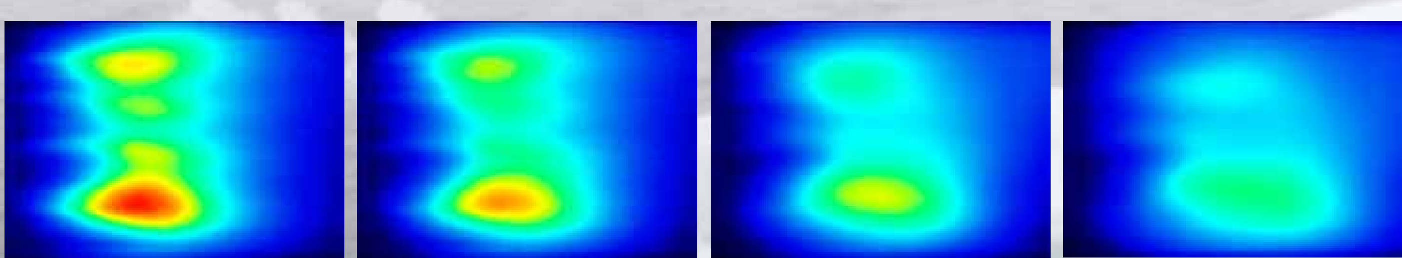
In 2013, the Task has strengthened its position in high pressure combustion technologies by further extending the application of oxy-fuel from gas turbine to coal fired processes.

The PhD work focused on optimizing pressurized coal combustion to reduce capture penalty, while the High Pressure Oxy-fuel Combustion infrastructure (HIPROX) was awarded funding for expansion to use solid fuel (framework of the European Infrastructure ECCSEL). Further work on coal process within our third party collaboration with Mälardalen University/KTH, showed that a more extensive cryogenic purification of the flue gases combined with less demanding oxygen purity from the Air Separation Unit can yield a significant benefit in terms of electrical efficiency.

Combustion testing under high pressure at DLR showed that the FLOX® burner concept allows to beneficially increasing the CO_2 concentration in the exhaust gas up to 7 % and 9 % at 5 and 10 bar, respectively, in post-combustion capture with Exhaust Gas Recirculation (EGR). The concept appears to generate better flame behaviour compared to the previously tested swirl burner technology.

The HIPROX facility was in 2013 rented to a Gassnova demo project. However, an improved fully optically accessible combustor has been designed and constructed which will solve the initial problems encountered during commissioning. This better arrangement will be the basis of the experimental work in 2014.

Finally, applying EGR to a pre-combustion capture process has been suggested and the first order evaluation indicates that the idea is promising to circumvent the problem related to high NOx emissions from hydrogen fired gas turbine. This concept will be further developed and studied in 2014. Four journal papers have been published in 2013 from the Task.



a - 10 % EGR | b - 150 % EGR | c - 20 % EGR | d - 25 % EGR

Combustion visualisation of FLOX® burner at 5 bar pressure with increasing Exhaust Gas Recirculation rate in the DLR facility.

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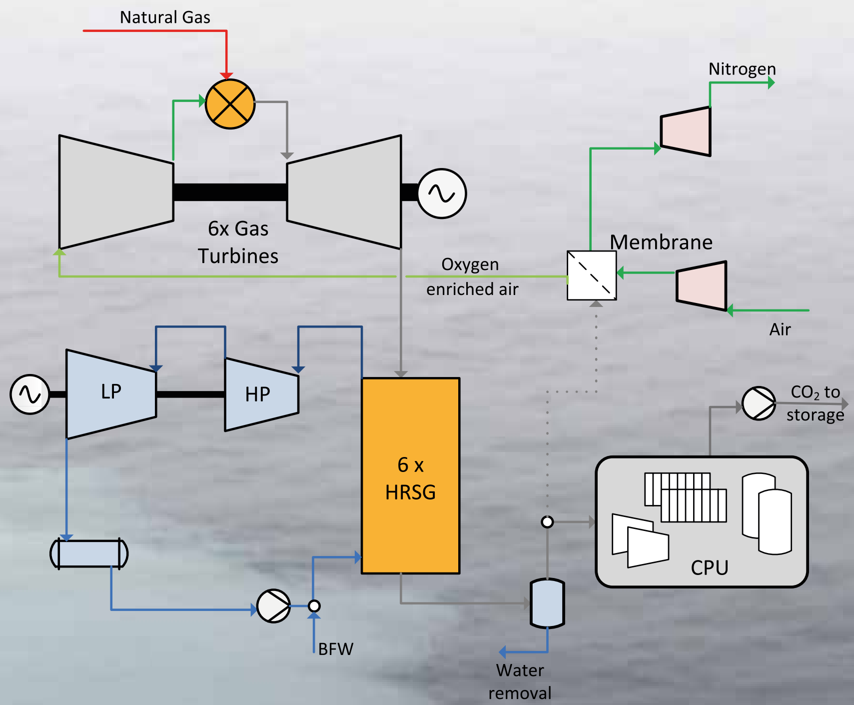
Application to industry and off-shore (1.5)

The principal focus of the task in 2013 was in dveloping systematic methodologies for integrating novel CO_2 capture technologies for industrial and off-shore emmissions and studying the potential of different capture routes for two case studies: CO_2 capture from off-shore gas turbines and CO_2 capture from fired heaters in refineries.

As a part of the systematic methodologies, a novel hybrid membrane-low temperature process was developed for post-combustion CO_2 capture.

For off-shore gas turbines, the emphasis was on identifying technologies that with no gas-liquid inteface and that would lead to a reduced foot-print and weight. The different options considered were supersonic gas expansion, high temperature dual phase membranes and different oxy-combustion and enriched air concepts.

The feasibility of retrofitting existing furnaces in refineries with oxy-combustion capture was tested experimentally in the lab. The experiments were conducted to verify if the temperature and heat flux profiles are similar when converting from air combustion to oxy-combustion and the CO_2 recycle required. The feasibility of retrofitting existing furnaces with H_2 combustion was tested by developing new low NO_x H_2 burners. This is part of a PhD activity associated with this task.



Process schematic for a novel enriched air EGR cycle

BIGCCS

Integrated assessments (1.6)

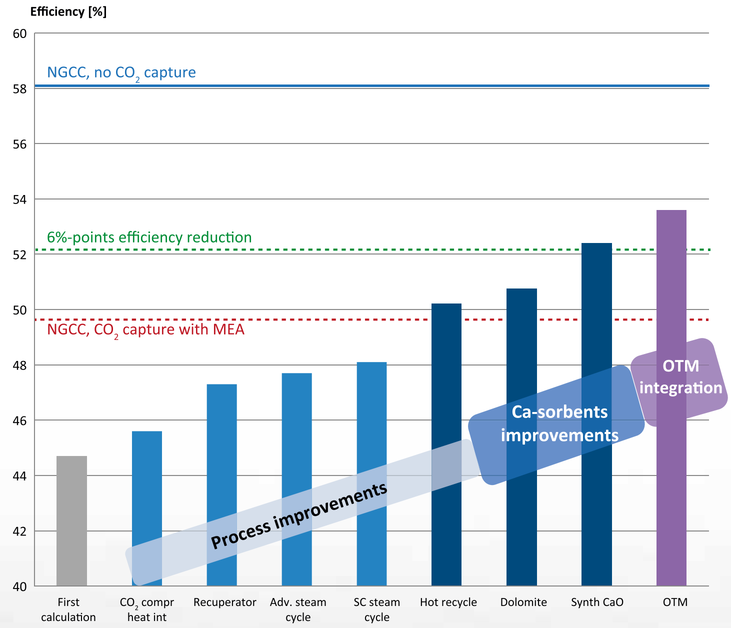


Figure 1. Process efficiency for different Ca-looping integration options and Ca-based sorbents.

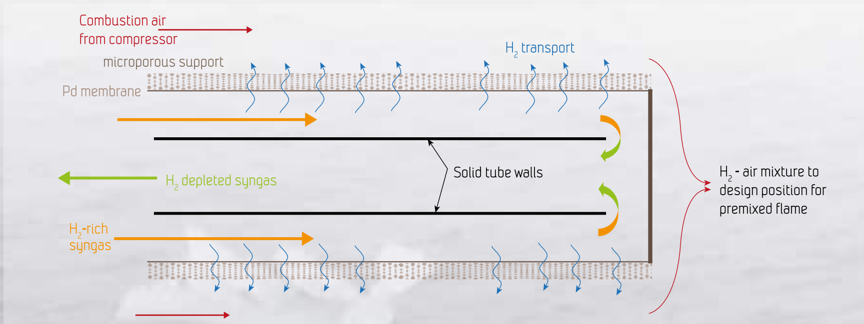


Figure 2. Fuel injection scheme with hydrogen distribution through a porous wall

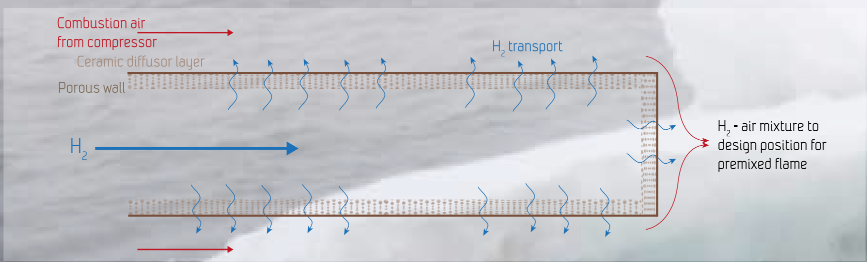


Figure 3. Fuel injection scheme with hydrogen separation and distribution using a palladium membrane.

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$CaO/CaCO_3$ looping (a.k.a. Ca-looping or carbonate looping): Process simulations were continued for how to apply this technology in natural gas combined cycles in the most efficient way. A synthesis of the work was presented during the PCCC2 conference in Bergen in September 2013, and during the BIGCCS consortium day. In summary, process simulations revealed that in theory capture penalties lower than 5 %-points are possible with this capture technology (Figure 1), but at the cost of a very complex integrated power and capture process.

In order to support the already ongoing collaboration between tasks 1.2 and 1.3, process simulations were conducted for the IGCC with distributed fuel injection of hydrogen in the combustor, i.e. a fuel injection scheme where the hydrogen fuel diffuses through a porous wall (Figure 2) or a membrane (Figure 3), to obtain best possible mixing with combustion air. The IGCC process was simulated for two different fuel injection schemes, and the results showed an efficiency improvement of 0.7-1.4 %-points (which is quite significant) compared to a reference case IGCC.

Furthermore in task 1.6 a spread-sheet based heat-and mass balance model was established for Chemical Looping Combustion (CLC). The model is very flexible and can determine overall heat and mass flows for different materials that can be envisaged for CLC. With this model as a basis, collaboration will be initiated between tasks 1.6 and 1.7 during 2014, with the aim to analyze results from the BIGCCS Task 1.7 hot CLC rig, and further on to use experimental results as a basis for overall process simulations with CLC.

Chemical Looping Technologies (1.7)

Chemical Looping Combustion (CLC) is a novel and promising CO_2 capture technology which has a large potential with respect to efficiency and CO_2 capture cost.

Main challenges in CLC are:

- Oxygen carriers with high enough oxygen capacity and mechanical strength.
- Raw materials and production processes for large scale oxygen carrier production.
- Reactor systems with sufficient oxygen carrier transport capacities, sufficient residence times, and control logics in order to control the process in a safe and desired manner.

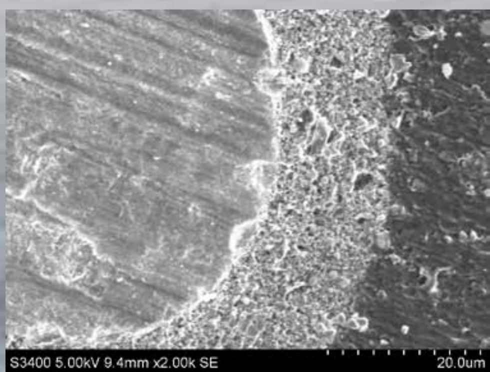
The CLC deals with these topics. SINTEF Energy Research works on a 150 kW fluidized bed reactor system, SINTEF Materials and Chemistry works on oxygen carrier development, and NTNU is involved in the development of control system for the 150 kW rig.

The project has developed a CMT (Calcium-Manganese-Titanium) oxygen carrier. To reduce the number of steps and costs for particle production a method using direct granulation of precursors ($CaCO_3$, Mn_3O_4, TiO_2) has been tested. The first batches of material were produced in 2013 and tested in a 3 kW reactor. This reactor set-up was constructed in 2012 and started up for the first time last winter. The testing shows that a greater strength is needed for the material produced indicating use of higher calcination temperature or longer calcination duration.

When these small-scale tests show satisfying results for an optimized CMT oxygen carrier it will be produced in larger quantities and tested in the 150 kW reactor system. The 150 kW rig was finalized during last winter (2013/2013) and the first tests were performed in March and April, 2013. These tests were still at low temperatures in order to check system functionality and oxygen carrier transport between the reactors. Based on the recorded pressure curves and the oxygen carrier losses in the back filter, the tests were judged as being successful. The rig has now been transported to Trondheim where it will be mounted during March-April 2014 and CLC tests at relevant temperatures will start.

The EU FP7 project ”SUCCESS” coordinated by the Technical University of Vienna is progressing well. SINTEF is partner together with 14 others which are all among the most active within CLC in Europe. Project kick-off with all partners was held in Vienna in September, 2013. Task 1.7 activities and infrastructure established was instrumental in becoming a partner of this EU project.

Support material coated with oxygen carrier material for chemical looping combustion.



Cross-section of support material coated with oxygen carrier material.

BIGCCS

CAMPS (1.8)

The CAMPS Task builds on international collaboration between SINTEF Energy Research and world-leading institutions in the US within the area of combustion.

A primary objective of CAMPS is the development of next-generation high-fidelity design tools for CCS-related combustion technologies. More specifically, the research focuses on technical challenges related to optimization of combustion processes in large, state-of-the-art gas turbines and coal furnaces for power generation.

In 2013 a US-Norwegian network for combustion modelling and simulation was established through CAMPS, based on the collaborative ties between SINTEF and US institutions such as Sandia National Laboratories, UC Berkeley, and Stanford University. A one-year stay at Stanford University was completed by one SINTEF researcher in August 2013, while another long-term stay at Sandia National Laboratories (10 months) started up in October 2013. In addition, there have been several short-term visits to UC Berkeley and Sandia National Labs.

Through the collaboration with Stanford, work on oxy-combustion of pulverized coal has been carried out with a focus on char gasification and oxidation. This work has led to improved models for describing particle-fluid interaction of porous reacting particles relevant to oxy-combustion concepts. At Sandia National Labs in Livermore, California, Direct Numerical Simulation (DNS) applied to hydrogen-fired gas turbine combustors has been performed. The DNS results provide both insight and validation of databases for the development of full-scale models for hydrogen-fired gas turbines. Through the collaboration with UC Berkeley, preliminary estimates of turbulent flame speeds for premixed H_2 combustion was obtained for a range of pressure and equivalence ratios relevant to gas turbine combustors. This work was performed by the use of a 1D combustion code provided by UC Berkeley and based on the Linear Eddy Model developed by Dr. Alan Kerstein (formerly Sandia). Dr. Kerstein is currently engaged as a part-time consultant at SINTEF Energy Research and is tightly involved in the research activities within CAMPS. A central collaborative effort with Dr. Kerstein has been the development of LEM3D, a novel approach towards a high-fidelity combustion design tool. In 2013, salient features of differential diffusion effects in a hydrogen-rich jet were demonstrated using the LEM3D model.

Collaborators gathered at UC Berkeley, April 2013.
From left: Alan R. Kerstein (consultant), Sigurd Sannan (SINTEF), Prof. J.Y. Chen (UC Berkeley), Prof. Robert W. Dibble (UC Berkeley), Andrea Gruber (SINTEF), Andrew North (UC Berkeley).

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

CO_2 pipeline integrity (2.1)

The main objective of this task is to develop a numerical model that can be used to ensure limited damage to a CO_2 pipeline in case of a pipeline rupture.

This will enable safe and cost-effective design and operation of CO_2 pipelines. The main modelling challenge lies in describing the complex dynamics and interaction of the fluid and the fracture process.

In 2013, a framework for comparing the developed model to the existing empirical framework was established. Results show that the empirical framework was highly non-conservative in the prediction of required pipe thickness for the case studied. These results were presented at two different conferences, TCCS-7 conference in Trondheim (with an accompanying paper in Energy Procedia) and a presentation at the international "4th Transportation of CO_2 by Pipeline" conference in Newcastle (UK). In addition, a journal article written in 2012 on the incorporation of dry ice in thermodynamic calculations was published.

Some first steps in getting access to some of the very few existing experiments on crack arrest in CO_2 pipelines were also made in 2013. This is work in progress, but the signs are positive that such access will be provided in 2014.

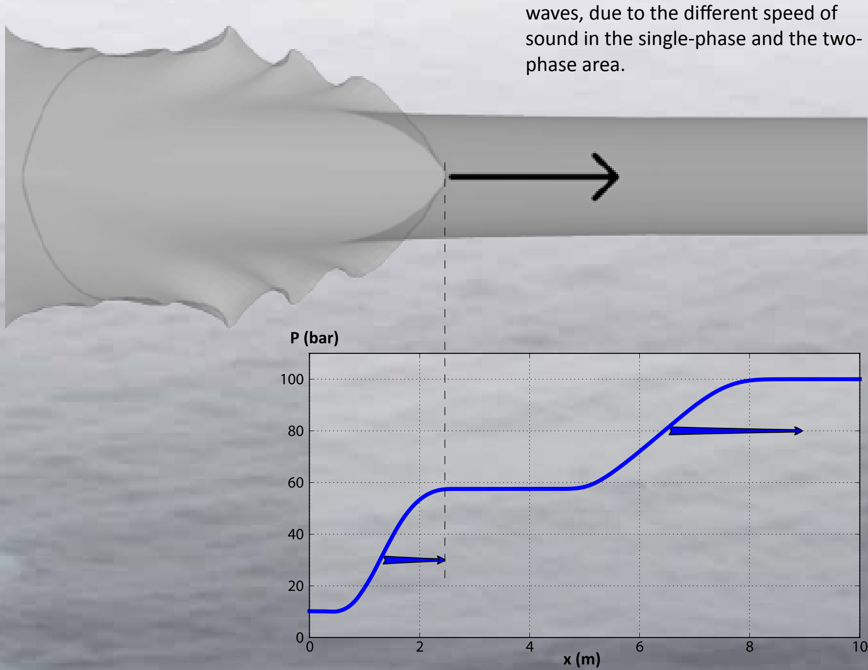
Progress has been made to further develop the 1D outflow model such that the 3D effects of the pressure distribution in an opening pipe can be simulated without considering the full 3D pressure field. In addition, the possibility to describe the thermodynamics of CO_2 mixed with nitrogen has been implemented in the coupled code. This will be essential when reproducing some of the full scale data that exists and that we might get sufficient access to.

A tool (LS-OPT) to systematically study the effects of different material parameters on the fracture velocity has been applied and has been accepted for presentation at the European Conference on Fracture (ECF20) in Trondheim. The results will also be published in a dedicated issue in Procedia Materials Science in 2014.

There are strong links between Task 2.1 and the new competence-building project "Ensuring well integrity during CO_2 injection", which is part of Task 3.5, Well integrity.

Illustration of the fracture race, subject of the investigations in Task 2.1.

The pressure plot has two rarefaction waves, due to the different speed of sound in the single-phase and the two-phase area.



CO_2 mixture properties (2.2)

CO_2Mix phase equilibrium setup

Approaching critical point in a CO_2/N_2 mixture

CO_2Mix phase equilibrium cell

In this task, nicknamed CO_2Mix, selected thermo-physical properties of CO_2-rich mixtures relevant for CCS are experimentally determined.

Specifically, phase state (i.e., the fractions of gas and liquid) at equilibrium, density, and speed of sound of CO_2-rich mixtures are measured. Such data are needed to calibrate thermodynamic models, which in turn are employed for designing and operating CO_2-capture and transport systems. Several important gaps have been identified in the measurement data found in the literature.

The work in CO_2Mix is performed by SINTEF ER, Ruhr-Universität Bochum (RUB), and NTNU. Two PhD candidates are educated. At RUB, a PhD candidate, Robin Wegge, was hired in October 2010, and he has started the work on the speed of sound and density measurements. At NTNU, another PhD candidate, Snorre Foss Westman, started in January 2013. He is performing phase equilibrium measurements.

In 2013, the main focus of the work was to complete and verify the experimental setups needed for the measurements. Measurements with the new phase equilibrium setup have started, and the results so far have been very promising. Measurements of density and speed of sound will start in the first half of 2013.

Two conference proceedings articles were published from CO_2Mix in 2013. The first measurements were presented at TCCS-7, with an accompanying proceedings article coming in 2014. In addition to the Consortium Day presentations, the work in SP2 was presented to the BIGCCS partners in two technical telephone conferences, taking place in April and November, respectively.

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Qualification and management of storage resources (3.1)

Large scale CO_2 flow models

During 2013 BGS have continued to investigate whether faults and fractures in the crests of the large Bunter Sandstone domes might cause leaks during CO_2 injection or storage.

This work aims to learn about the sealing properties of any faults by (a) investigating the pre-production gas column heights and the overpressures retained by seismically resolved faults above the gas-water contacts in the gas-bearing domes, and (b) by modelling the likely effects of realistic reservoir pressure rises on faults within the domes in general.

The Bunter Sandstone Formation is of interest to the CCS community since it has significant potential for injection and storage. It has an average thickness of 200 m, is overlain by fine-grained cap-rocks and possesses suitable reservoir properties for CO_2 storage. Halokinesis in the underlying Zechstein strata has produced periclines in the Bunter Sandstone which provide storage capacity for anthropogenic CO_2. The majority of these structures are water-bearing, but 8 gas fields have been discovered and faulted cap-rocks have been shown to retain gas columns in some of these Bunter Sandstone gas fields.

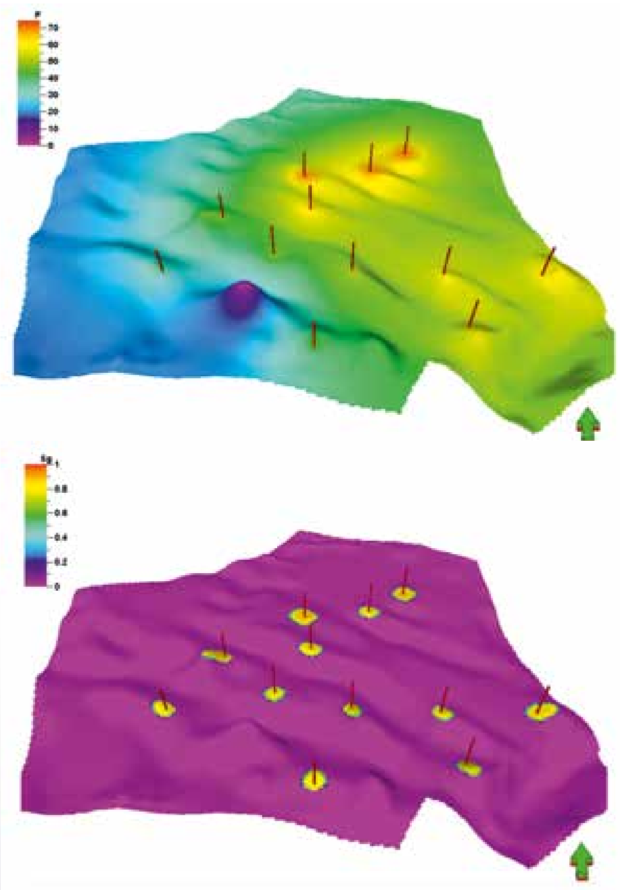
This work has led to a paper, submitted to Petroleum Geoscience which summarizes BGS work in the area for 2012 and 2013.

The flow modelling has followed the same injection strategy with 12 injection wells active over 50 year injection. Initially, the injection is limited by the fracture pressure at the wells and 1196 Mt of CO_2 can be injected. The upper figure shows the CO_2 saturation and pressure change following injection.

CO_2 storage with water production

When CO_2 is injected into a spatially confined porous underground aquifer the pressure will generally increase during the injection period. This increase of pressure should not exceed a certain level as the pressure increment can create new pathways for leakage from the storage unit. Apart from the option of closing down the injection well(s), or possibly drilling new injection wells connected to the existing infrastructure, another obvious remedy is to drill water production wells to relieve the pressure in the aquifer. Water producers can certainly be planned and implemented in the start of a CCS project, or initially be planned as a possible future option to serve as an insurance against unanticipated pressure build up. Such considerations are not yet at a mature state. Work related to this was presented at GHGT11, Kyoto, 19-22 November 2012. This has subsequently been published in the symposium proceedings in Energy Procedia 2013: Synergy benefits in combining CCS and geothermal energy production.

Simulations of storage of CO_2 with water production in a 5-spot pattern have been performed at SINTEF where injection pressure, horizontal permeability, and length of the producer perforation interval have been varied in a systematic manner. The model is written on dimensionless form, and the dimensionless groups identified. The amount of stored gas at breakthrough time is relative insensitive to perforation length and horizontal permeability, while showing a pronounced dependency on the gravity number. The higher injection pressure, the more is stored at time of breakthrough. Further work should address heterogeneity, and through atomization, simulations with more cases covering the dimensionless group



CO_2 saturation (upper) and pressure change (lowest) following injection of CO_2 at 12 injection wells. Injection is limited by fracture pressure at well location.

parameter space should be run. The simulation results could be used for future development of a proxy function suitable for quick assessment of planned storage projects, or as a component in a larger techno-economic model suitable for uncertainty analysis and optimization exercises.

Developments in basin modelling

A basin modeling approach has been suggested for simulating CO_2 storage scenarios. The motivation for using basin simulator is to have a "fit-for-purpose" model, which can perform quick assessments of the possible migration pathways within and in between potential storage formations in order to identify regions of the sealing formation and potentially model boundaries that warrants more careful investigation. The fast computation time makes this approach especially suitable for Monte Carlo simulations, and can hence be used for assessing risk and uncertainties trapping of CO_2.

The SINTEF in-house basin modeling software SEMI has been re-developed and adjusted for CO_2 storage assessment, and as a result: a SEMI CO_2 Demo version has been created. The main goal for this term has been to evaluate when, i.e. under which conditions and assumptions, this approach can be performed in a useful manner for CO_2 storage assessment. SEMI Demo currently includes mechanisms for trapping of free CO_2 in structural and stratigraphic traps, dissolution of CO_2 in the formation water within trap structures and migration loss.

One of the main questions has been to define which time window (i.e. major time step) this approach can operate on without severely violating the physical principles of CO_2 behavior within a carrier unit. Several options have been created within the simulator for setting migration speed for further calculating maximum migration distance within a time window. Based on tests on synthetic data sets, we then conclude SEMI Demo version will have difficulties mimicking the plume development during injection period, it should only be applied for long term assessment, some caution should be made for settings where the migration speed is low and migration distance to nearest trap structure is long, and it is suited for scenarios where traps are filled-to-spill and close to top seal break.

CCS GIS & database

At present the GIS-database contains data from the Northern North Sea area in Denmark, Norway and UK. The Northern North Sea is Europe's most prospective area for CO_2 storage and no GIS database covers this area as a whole. The EU GeoCapacity GIS is not public and data are not updated with respect to the Norwegian storage atlas data. On-going work in the NORDICCS Competence Centre includes a web-based CO_2 storage atlas for the Nordic countries. This makes the BIGCCS webGIS the only CCS database comprising the whole Northern North Sea.

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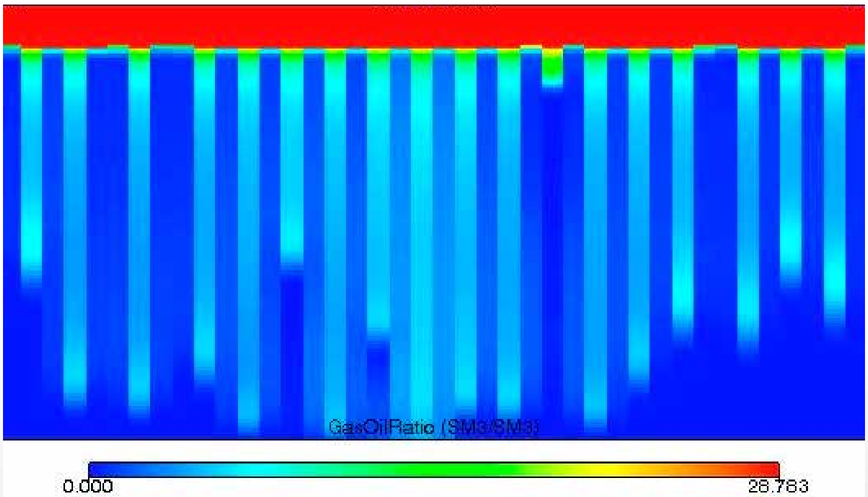
Storage Behaviour (3.2)

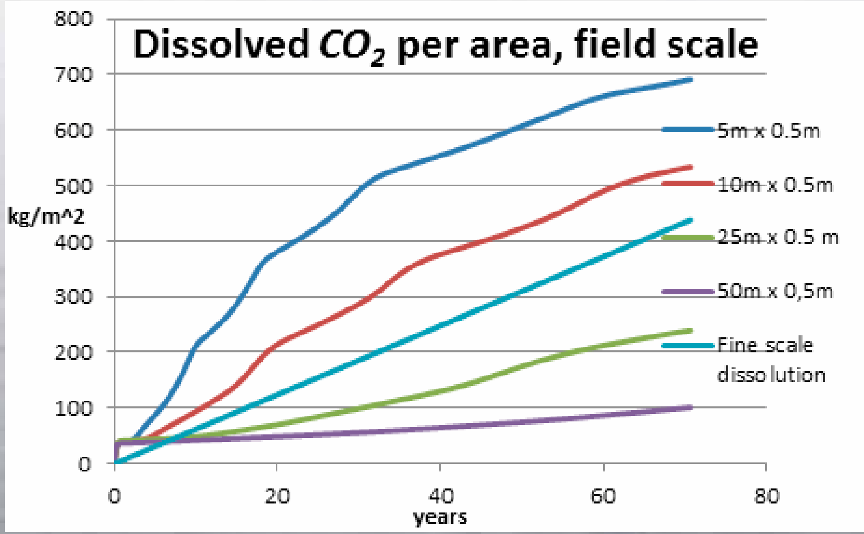
Dissolution of CO_2 in brine is a medium to long term trapping mechanism which is challenging to model in numerical field scale models. In particular, the so-called diffusion induced convection mechanism does significantly speed up the dissolution process, and a basic understanding of the process is important.

In 2013 most of the work connected to diffusion induced convection was completed. The main theoretical work was submitted in 2013 to SIAM Journal of Applied Mathematics entitled "The Gravitational Instability of a Diffusive Boundary Layer; Towards a Proof for the Values of Critical Times and Wave Numbers". Here, for the first time in the literature, a pertinent route to a rigorous mathematical proof of critical onset times and corresponding critical wave numbers has been given using the energy norm as instability criteria. The approach draws on recent theorems in functional analysis, and aims to end the discussion within this subject of what values the critical numbers really have.

In addition, work has been performed on the upscaling of this mechanism, as the numerical effect of having large grid blocks in field models generally impedes the onset of convective mixing, thereby underestimating the dissolution process. This work was presented at the Trondheim Conference in June.

Two PhD students have performed experimental and numerical work on both convective mixing and on capillary trapping, where the experimental work has been performed in 2D Hale-Shaw cells with visual observation of the process. Excellent agreement between experiments and numerical simulations were found. Also, preparations for experiments in heterogeneous Hale-Shaw cells were done in 2013, and both the PhD student plan to finalize their degree in 2014.





Dissolved CO_2 in field model shows strong dependency on numerical grid block size (lower figure). The plots (top figure) show cumulative dissolved CO_2 as function of time for the same physical model using different numerical spatial resolution. The reason smaller grid blocks give larger dissolution is that convective mixing is not hindered significantly, and that large grid blocks give numerical dispersion that over-predicts the dissolution rate.

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Monitoring, Leakage and Remediation (3.3)

Seismic monitoring

An advanced seismic imaging technique, acoustic Full Waveform Inversion (FWI), was applied to real Sleipner data from 2006 and 2008 with results indicating that the layered plume can be accurately imaged (see Figure 1). Within the monitoring task an elastic FWI code has been developed by a PhD candidate and synthetic time-lapse studies performed during the year show promising results.

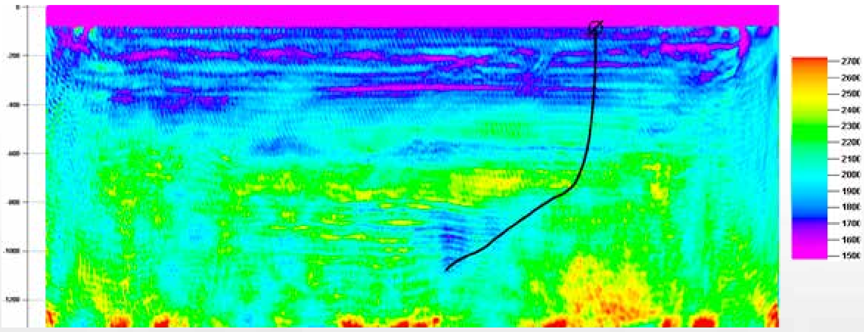

Figure 1: Interval velocity model in depth resulting from application of FWI to real 2008 Sleipner data

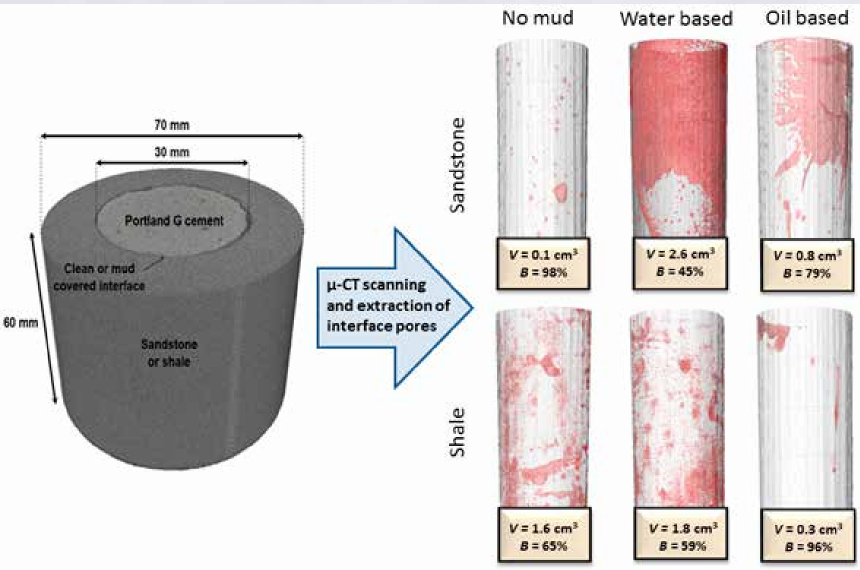

Figure 2: Geometry of samples with measures indicated (left), and extracted interface pores of each of the 6 samples (right). In the latter image, the interface pores are red – and they are quantified in terms of volume and bonding percentage.

Spectral decomposition has been used to discriminate between direct fluid substitution and pressure changes in the storage reservoir. The results show agreement with previous attempts, using different methods, to differentiate between CO_2 saturation changes and pressure increases in the Tubåen formation caused by injection. Results are also in line with on-going PhD work on applying AVO analysis at the Tubåen formation. A spin-off project on uncertainty quantification and reduction in integrated monitoring methods was approved by Research Council of Norway (RCN) and will be initiated early 2014.

Leakage

An experimental study was performed to investigate how ordinary well cement bonded with sandstone and shale formations. This was done by letting the cement set within hollow rock cylinders. Samples were prepared in such a way that the interface between cement and rock was either clean or covered with water-based mud or oil-based mud. The pores at the interface between cement and rock were extracted and quantified by using micro computed X-ray tomography (μ-CT), as seen in Figure 2. Here, V denotes the volume of the interface pores in each sample, while B denotes the bonding percentage. The latter is high if the cement is in direct contact with rock over a large area – and becomes smaller as interface pores are obstructing direct contact between rock and cement. Our work generated new knowledge on the actual sizes, 3D geometries and densities of micro-annuli at the cement-formation interface, and mapped how these vary with different formation types and mud types. This is important in order to prevent them, remediate them – and understand the risks they pose. The main conclusion from the work is that fluid choices made already during the drilling phase of a well will impact its long-term sealing ability.

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Fundamental effects of CO_2 on rock properties (3.4)

Loss of injectivity due to thermal stress and fracture initiation

This activity investigates the risk of fracturing a CO_2 reservoir close to an injection well due to the thermal effect of injecting CO_2, which is much colder than the ambient conditions downhole. These circumstances are not expected for pipeline transport of CO_2, but could occur if CO_2 is supplied by ship in liquefied form and is not sufficiently heated before injection.

Continuing the thermal stress simulations run in 2012, laboratory testing of thermal fracturing is in progress. Instead of cooling a rock sample in the form of a wellbore, a similar stress state may be achieved by heating a disc of the rock which is constrained diametrically. A first series of tests have shown that the inherent anisotropy in caprock shale material causes it to expand differently in perpendicular directions, suggesting that bedding angle relative to an injection well can influence the temperature contrast tolerated by the rock prior to developing thermal stress-related tensile cracks.

Laboratory testing of fault reactivation

A bespoke apparatus for investigation of the flow properties of fault gouge materials under changing stress conditions is now up and running at BGS. During injection of CO_2 into a storage reservoir the stress state in the cap-rock will gradual be altered. This alteration may results also in changes in the sealing properties of cap-rock discontinuities such as faults. A number of theoretical frameworks exist to address such issues, but very little experimental evidence is available. With the apparatus it is possible to expose thin patches of simulated clay-gouge material to slow (as slow as 1 mm every 3 months) shear stress while being subjected to varying normal load.

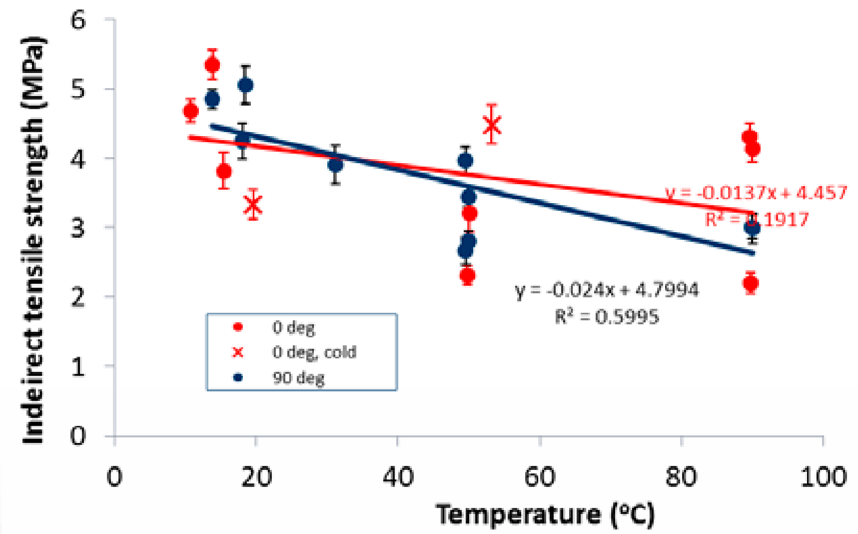


Figure 1: Laboratory test campaign showing strength reduction in shale specimens on heating. Analysis of the data suggests that thermal tensile stress develop differently according to bedding plane orientation of the shale, wrt to the well axis.

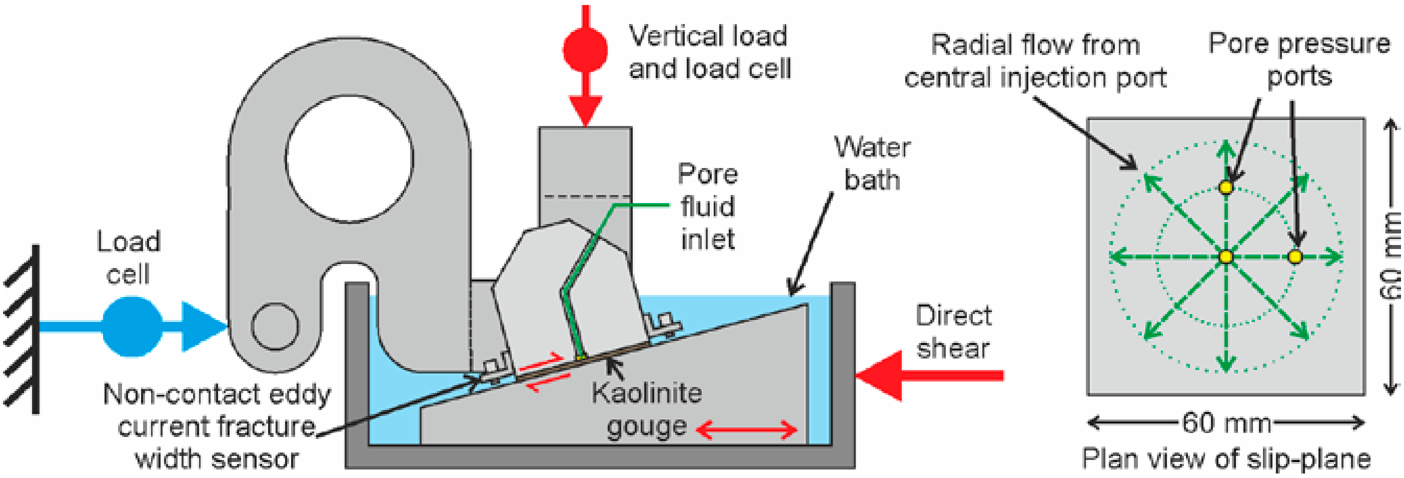
The first test programme has looked at the effect of loading-unloading-reloading on a kaolinite gouge. The recorded flow properties during the 44 steps of the test are shown in the figure on the next page. Considerable hysteresis in the flow properties can be observed, and the flow is progressively reduced, indicating the importance of the stress history. However, as the gouge in the first test ended up very thin, some effort will be made to find better materials for the next tests.

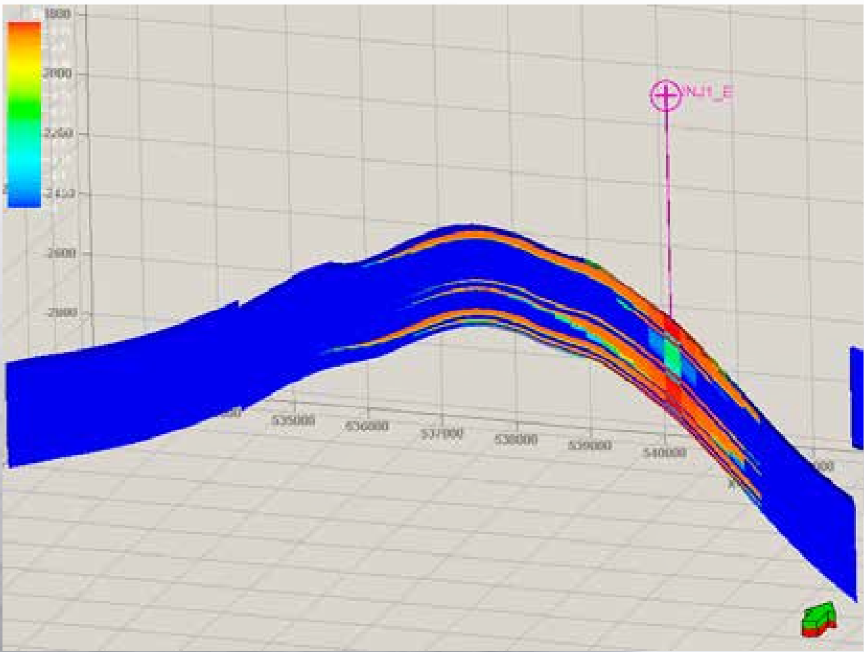
Figure 2: Tensile testing with compression perpendicular and along bedding planes to the well axis.

Caprock properties and the effect of intra-formational sealing layers

Thin layers of mudstone and clay in a CO_2 reservoir may have a significant effect on the flow of injected CO_2, especially if they extend over large areas. Even small-scale heterogeneity has implications for how the CO_2 is distributed and trapped in sedimentary sequences. To investigate such effects, simulations work has been performed on carefully prepared fine-scale 2D models of cross-bedded shallow marine and tidal sands (figure above). The simulations investigate

Overview of apparatus





Reservoir section 12 km length, 325 m thickness, with injection into layered reservoir with continuous sealing layers. This architecture distributes the CO_2 flow and increases filling efficiency.

filling and drainage of the fine-scale bedding structure as CO_2 is first injected and then over time migrates to the top of the storage formation.

Sealing characteristics

Exposure to a CO_2-rich environment may alter the wetting properties of reservoir and caprock, reducing the resistance towards entry of CO_2. To investigate the extent of such changes, experiments are conducted to measure the flow properties of low-permeable rock samples both before and after exposure to CO_2. During 2013, testing was performed on a low-permeable sandstone sample from the Stø formation in the Nordkapp basin. Additionally, efforts were made to find a core sample that is representative of a caprock sequence and that has been sufficiently well preserved. A mudstone sample from the Nordland group was selected and has undergone initial measurements of permeability. Reliable measurements are difficult to obtain in samples of low permeability, so it has been essential to design and build an improved experimental set-up to measure the capillary entry pressure.

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CO_2 Chain Analysis and Assessment of Environmental Impacts and Safety (4.1)

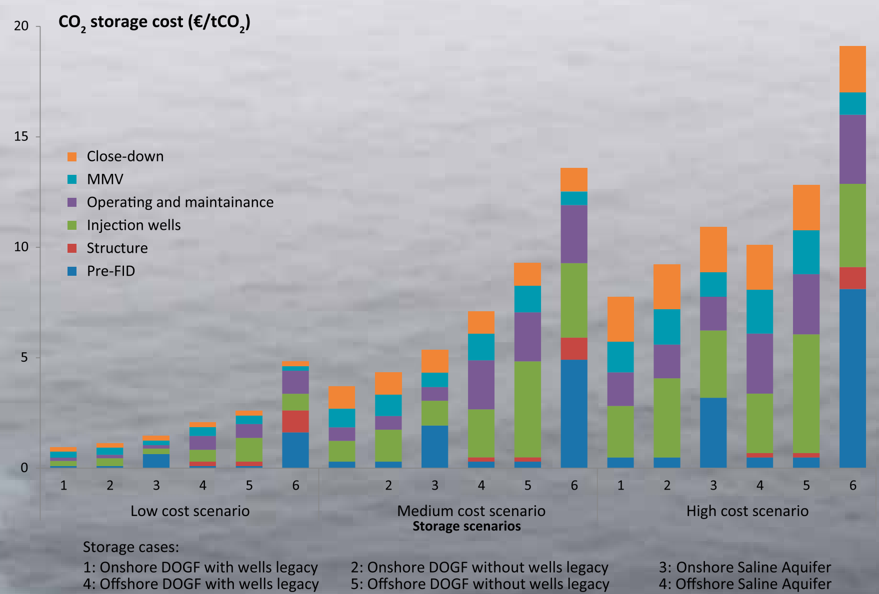
One of the main objectives of this task is to develop methods for assessing CCS value chains and to determine cost-effective, environmentally friendly, and safe options for CCS.

In 2012, this task developed even further the methodology for such a multi-criteria assessment of CCS chains. This methodology involves designing CCS chains using a ”modular” approach where each part of the chain – capture, transport, and storage – is treated as its own module and can be connected in various ways to create CCS chains to study in detail. This approach is thus flexible and can be used to answer a variety of important questions surrounding CCS. The focus in 2011 and 2012 was on developing the capture module for post-combustion amine capture and transport via onshore pipelines and shipping while in 2013, modules for transport for off-shore pipelines and shipping and storage in Saline Aquifer and Depleted Oil and Gas Field have been created and tested on simple case studies.

The techno-economic modeling utilizing Aspen HYSYS or information available in the literature and Aspen Economic Analyzer have been combined in a consistent manner with input-output life cycle assessment (LCA) methods to ensure complete consistency. The methodology and the newly-added transport modules were illustrated through a simple case study to illustrate and compare the technical, economic, and climate impact performances of an offshore pipeline versus CO_2 shipping to an offshore site for a wide range of distances and CO_2 capacities. This type of assessment and case study has provided new insight on transport technology selection, influence of parameters on the selection, transport costs and impact of financial risks on technology selection. This case study has been submitted and accepted to the International Journal of Greenhouse Gas Control.

In addition, storage modules were also developed to represent the technical, the economic, and the life cycle assessment of CO_2 storage in Saline Aquifer and in Depleted Oil and Gas Field based on the Zero Emission Platform CO_2 storage report. In addition of six possible storages, three costs scenarios are considered, leading to a total of 18 pre-set cases as shown in the Figure. Finally, several parameters are included to customize the model to represent specific storages.

CO_2 storage costs of the 18 pre-set cases in the CO_2 storage module.



Economic and Policy Incentives for the CO_2 Chain (4.2)

A main objective of this task is to explore economic and policy barriers to CCS development and deployment, as well as policy tools that can overcome such barriers. Two important issues in this regard are the value of CCS and factors driving public perceptions of CCS.

Earlier economic studies on CCS have not considered the tension between the benefits of CCS and the costs associated with the possibility of leakage of CO_2 from geological storage sites. The scale at which CCS should be deployed must also be seen in light of future costs if CO_2 leakage should occur.

A dynamic economic model of allocation of CO_2 reductions is introduced to analyze these issues, including CCS with a possibility of leakage from geological storage sites. To the extent that CO_2 leakage rates are uncertain and causes delayed temperature increase, correct pricing of CO_2 storage (and CCS) requires that present CO_2 emissions captured through CCS to be offset more than proportionally. This means that the value of mitigating one ton of CO_2 through CCS is less than mitigating one ton of CO_2 through e.g. replacing coal power with wind power.

Present carbon pricing may not reflect the fact that firms or states responsible for stored CO_2 do not internalize remediation costs that may occur in the future.

Presently a low and uncertain CO_2 price, related to a lack and uncertain climate policy, is a major obstacle to investments in CCS. The introduction of a CO_2 price floor guaranteed by government has been suggested as an effective policy tool to stimulate CCS investments.

A real-option based modeling framework was developed to analyze the effect of a CO_2 price floor on CCS investments, as well as the responsiveness of various CCS chain variants.

A real options framework allows for explicit modeling of timing and delay of irreversible investments in power capacity and CCS, uncertainty of important variables such as the CO_2 price, and the option value of delaying investment to learn and thus reduce uncertainty.

A flexible operation of CO_2 capture, which is relevant for post-combustion CO_2 capture, has an additional value if the power price is high and/or the CO_2 price is low, since temporary shut-down of the CCS facility will save power and running costs, even though CO_2 allowances must be bought to compensate emissions. In addition temporary CCS shut-down will release power to the market and may thus eliminate the need for additional generation investments and increase profits in periods of high power prices.

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BIGCCS animation movie – QR

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Research Institutes:

- BGS - Natural Environment Research Council
- CICERO Center for International Climate and Environmental Research – Oslo
- Deutsche Zentrum für Luft- und Raumfahrt
- GEUS - Geological Survey of Denmark and Greenland
- Geological Survey of Norway (NGU)
- NTNU Social Research AS
- SINTEF Petroleum Research AS
- SINTEF Foundation

Universities:

- Norwegian University of Science and Technology
- University of Oslo
- TU München by Lehrstul Für Thermodynamik

Industry:

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The FME Scheme

The Centres for Environment-friendly Energy Research (FME) scheme is an initiative to establish time-limited research centres conducting concentrated, focused, and long-term research of high international calibre in order to solve specific challenges in the field of energy and environment. The centres were selected early 2009 via a detailed review process administered by the Research Council of Norway.

Two main assessment criteria formed the basis for the selection of the FME's relevance and potential for innovation and value creation, and scientific merit. One prerequisite for achieving the status of FME is that the centres consist of a distinct combination of researchers, research institutions, organizations, industry and private enterprises. The FME's receive NOK 10-20 million annually from the Research Council of Norway for five years, with a possibility for a three year extension.

The FME scheme is a direct follow-up of the broad-based political agreement on climate change policy adopted by the Norwegian Parliament in 2008, and of the national R&D strategy Energy21 of that same year.

More information about the FME scheme can be found at: www.forskningsradet.no/energisenter

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The Research Council of Norway