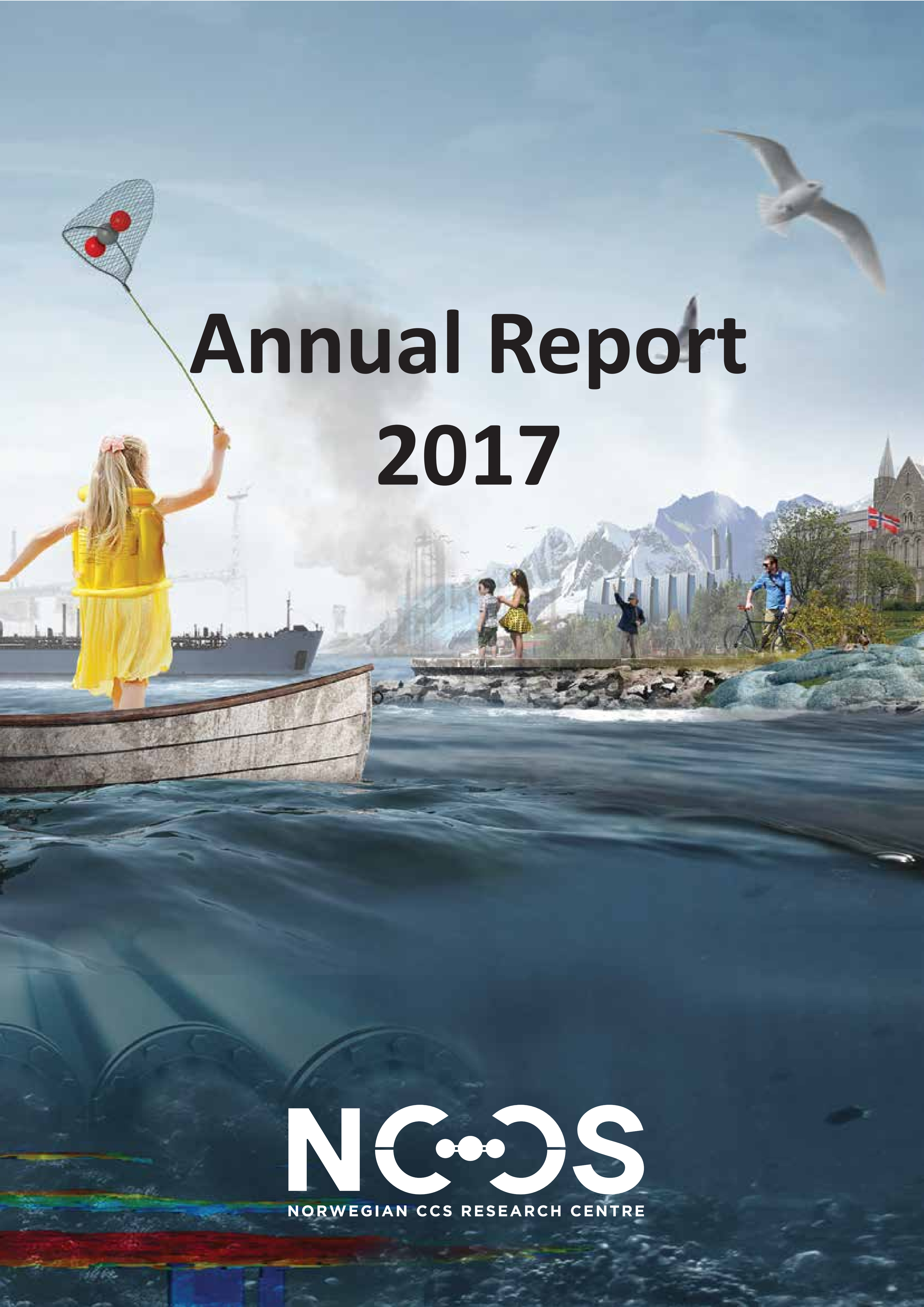


Annual Report 2017

NCCS

NORWEGIAN CCS RESEARCH CENTRE

NCCS

CO_2 capture, transport, and storage (CCS) is a process where waste carbon dioxide (CO_2) is captured from large industrial plants, transported in pipelines or ships, and deposited so it will not enter the atmosphere (like in an underground geological formation). EU energy and climate targets cannot be met cost-effectively without CCS, while making sure we have enough energy to go around.

NCCS (Norwegian CCS Research Centre) is a Centre for Environment-friendly Energy Research (FME). NCCS aims to fast-track CCS deployment.

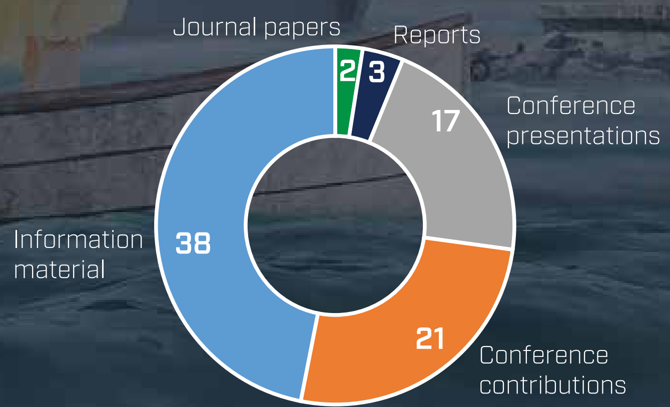
How can NCCS help? NCCS aims to fast-track CCS by working closely with the industry on research topics designed to address major barriers in making CCS happen in Norway, Europe, and the world. NCCS research focuses on two "CCS Deployment Cases": CCS for Norwegian Industry and Storing Europe's CO_2 in the North Sea. Researchers focus on tasks related to the CCS technologies for the Norwegian full-scale case, and seek to find clever ways to integrate capture with transport, and with storage. Any ways to reduce the cost of CCS will be a savings for each taxpayer! There is a huge potential in the North Sea to store CO_2 from all over Europe, and NCCS will unlock this potential through dedicated research that has been pointed by the industry as addressing key barriers.

26 partners
7 associated partners

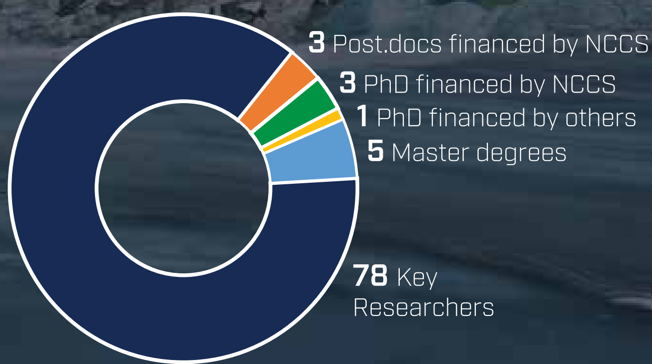
8 years

48.8 million

Publications



Personnel



Contents

Message from the Director

Dear partners and friends of the Norwegian CCS research centre

In NCCS, we fast-track CCS deployment by joint effort from academia and industry, performing relevant CCS research in world-class ECCSEL research infrastructure along the whole CCS chain. We do this because we believe that CCS is a key technology that is needed to reduce CO_2 emissions in a scale that makes it plausible to reduce man-made CO_2 emissions enough to limit global warming to less than two degrees compared to pre-industrial temperatures.

Through the two deployment cases, NCCS links both to the Norwegian full-scale project and the possibility to expand this into a large CO_2-storage facility receiving Europe's CO_2. 2017 has been an extremely exiting year, starting up the full machinery of the Centre. The achievements of NCCS so far is the result of clever and targeted work of my very skilled colleagues in the Operation Centre, the vise guidance from the Board lead by Dr. Per Ivar Karstad from Statoil, and the efforts made by all others involved in NCCS.

In 2017, we produced 74 deliverables, we added two new competence building projects (KPNs) expanding the total budget with NOK 20 million, and we started six new PhD/Postdoc candidates. Furthermore, we continued holding leading positions in organizations spearheading CCS development in Europe, and we have put significant efforts in communicating our achievements.

The interaction between industry, both users and vendors, the researchers, professors and PhD/Postdoc students, as well as the Research Council of Norway, is the fundament for our achievements. Thank you so much for your dedication and efforts!

Mona J. Mølnvik

Dr. Mona J. Mølnvik is the NCCS Centre Director. She has been with SINTEF for 20 years, and has been active in CCS research since the early 2000s.

Mona holds a PhD within mechanical engineering from NTNU and is Research Director for the Gas Technology department at SINTEF Energy Research.

She was central in developing and leading the centre of excellence, FME BIGCCS - International CCS Research Centre (2009-2016). Further, she has been involved in several EU-projects.

Mona has been a central contributor to development of CCS research strategies, and she was the first leader of the CO_2 transport initiative under EERA JP Carbon Capture and Storage.

Message from the Chairman of the Board

The UN Sustainability goals will require a balanced solution for both economic growth, food security, reliable energy supplies and reduced emissions of climate gases to the atmosphere to provide increased welfare to the global population. The transition toward a low carbon energy system is a major challenge for our society. This energy transition will require a set of new technological solutions, such as renewable energy, energy storage, low carbon transport solutions and carbon capture, utilization and storage.

Carbon capture, utilization and storage is a feasible and cost-efficient solution to combat climate change compared to other solutions. It is the only solution to cut emissions from many industrial sources, industries that produce key products to our society. However, the cost has to be reduced further.

NCCS is a key competence and research center, already contributing with new technological solutions to ongoing development projects. The ambition is to develop new technological solutions to reduce costs significantly for future development projects. This is important to deliver cost efficient solutions for a low carbon future, ensuring the long-term welfare of our society.

The first year of research have set the scene and direction. Now it’s time to deliver CCS technologies for future low-cost CCS projects.

Per Ivar Karstad

Dr. Per Ivar Karstad is currently working as project manager in the Statoil Research and Technology unit.

Per Ivar has more than 25 years of experience from the oil industry, both from field operations, business development and technology development.

Since 2011, he has been heading up several CCS development projects in Statoil such as Technology Center Mongstad, the Norwegian CO_2 Storage project (Northern Lights) and a number of CCS research projects.

Centre Manager
Amy Brunsvold

Dr. Amy Brunsvold is the Centre Manager of NCCS and a Research Scientist at SINTEF Energy Research.

She has almost 10 years of experience working in R&D related to CCS and natural gas, touching on topics from techno-economic assessments of CO_2 value chains, heat transfer in liquefied natural gas heat exchangers, and CO_2 transport with impurities.

Amy has a Ph.D. in experimental physical chemistry from Montana State University where she focused on molecular beam reaction dynamics and energy transfer at high-energies, with applications to materials and low Earth orbit chemistry. As a post-doctoral fellow at UC Berkeley, she studied the dissociation dynamics of free radicals related to combustion chemistry.

NCCS in a nutshell

CO_2 capture, transport, and storage (CCS) is a process where waste carbon dioxide (CO_2) is captured from large industrial plants, transported in pipelines or ships, and deposited so it will not enter the atmosphere (like in an underground geological formation). EU energy and climate targets cannot be met cost-effectively without CCS, while making sure we have enough energy to go around.

The feasibility study from July 2016 shows that CO_2 capture is technically feasible at three industrial emission sites in Norway capturing CO_2 from: Norcem, Norway's sole cement producer, Yara, the world's largest ammonia production company, and Klemetsrud, Oslo's waste management and energy recovery project. All three of these sites are currently conducting concept studies. They are planning to transport CO_2 by ships from the point of emission to an onshore facility connected to the storage facility. The CO_2 will be stored in the Smeaheia area east of the Troll Field in the North Sea.

How can NCCS help? NCCS will aim to fast-track CCS by working closely with the industry on research topics designed to address major barriers in making CCS happen in Norway, Europe, and the world. NCCS research focuses on two "CCS Deployment Cases": *CCS for Norwegian Industry* and *Storing Europe's CO_2 in the North Sea*. Researchers focus on tasks related to the CCS technologies for the Norwegian full-scale case, and find clever ways to integrate capture with transport, and with storage. Any ways to reduce the cost of CCS will be a savings for each taxpayer! There is a huge potential in the North Sea to store CO_2 from all over Europe, and NCCS will unlock this potential through dedicated research that has been pointed by the industry as addressing key barriers.

One of the most important tasks in NCCS is to train master and doctoral students in CCS research so they are willing and able to transfer this knowledge in future work, whether they work in industry or as researchers. The goal is to produce 24 PhDs, five postdocs, and 80 Master candidates.

Fast-tracking CCS is a joint effort. NCCS is a collaborative project between over 40 partners in industry, research institutes, universities, and other organizations, in 10 countries and on three continents. NCCS is led by SINTEF Energy Research in Trondheim.

As an industry-led Centre in the start-up phase, most of our efforts have been on communicating and integrating with the industry partners to align the research tasks with the industrial challenges related to CCS. Each task has a "family" with members who are actively engaged in the task and contribute to the development of the work plans and in the research activities. Research in NCCS is organized in 12 Tasks that together cover the whole CCS chain. The tasks address critical challenges for realizing CCS for Norwegian industry and storing Europe's CO_2 in the North Sea. In addition, efforts have been made to ensure dialogue with the Norwegian full-scale project.

International cooperation is of essence to NCCS. We hold leading positions on the strategic arena, like in the European Energy Research Alliance (EERA), and in the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). Furthermore, we are collaborating in several Horizon 2020 and ACT-ERA-net co-fund projects, and we are pursuing many new project calls.

NCCS Consortium Days 2017 were held in Trondheim with over 60 participants present to hear the latest results and discuss the outcomes. As of December 2017, NCCS has added 81 contributions to the Cristin publications database.

Vision and Goals

NCCS will enable fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects, aiming at becoming a world-leading CCS centre.

NCCS is a world-class national and international multi-disciplinary CCS partnership between operators, vendors and academia that have united to address one of the greatest challenges of our time: climate change. Capacity is built to capture, transport and store billions of tons of CO_2 by fast-tracking CCS deployment. NCCS is a dynamic, forward-looking approach that will maximize new and current knowledge to make CCS happen – in time to meet EU climate targets. CCS in the North Sea Basin has the potential of becoming a 50,000 billion NOK profitable business.

Goals

The overall objective is to fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects, aiming at becoming a world-leading CCS centre.

NCCS supports and aligns with the Norwegian full-scale CCS project to realize the Government's ambition to have this operational in 2020. This includes addressing technical and legal barriers via targeted research covering the full CCS chain.

NCCS develops science-based strategies for large-scale CO_2 storage and is a key facilitator for storage in the Norwegian North Sea Basin. This includes aligning with European CCS projects, while addressing technical and legal barriers via research on the full CCS chain.

Tangible objectives:

- Establish reliable prediction of storage capacity and prove strategies to ensure storage integrity.
- Enable qualification of specific CO_2 EOR projects on the Norwegian Continental Shelf.
- Ensure CO_2 transport and North Sea storage infrastructure qualified as European Projects of Common Interest (PCI – an instrument to help create an integrated EU energy market).
- Establish an engineering toolbox for CO_2 pipeline and well design.
- Establish CCS as a competitive, low-carbon technology in power generation and industry.
- Contribute more than 50 innovations for use in industry.
- Complete 24 PhD theses, with 50% of the candidates employed by an NCCS partner.
- Contribute 500 papers to peer-reviewed scientific journals.

Scientific objective:

Provide a frontier knowledge base for the technology breakthroughs required to fast-tracking full-scale CCS, with industrial relevance, by use of decision gates and priorities of the NCCS industry partners.

Innovation objective:

- Fulfil the commercial ambitions and needs of industry and society, while maximizing innovation in deployment cases.
- Establish a targeted spin-off programme for the execution phase of innovation processes and their faster adoption.
- Establish new research projects within topics where knowledge gaps are identified. As part of the innovation process, design a comprehensive IP strategy.

Recruitment objective:

Recruit and educate young people, reflecting gender balance and equal opportunities, with first-class competence in CCS-related topics (24 PhDs, 5 postdocs, 80 MSc graduates) to ensure recruitment to both industry and research institutions.

International objective:

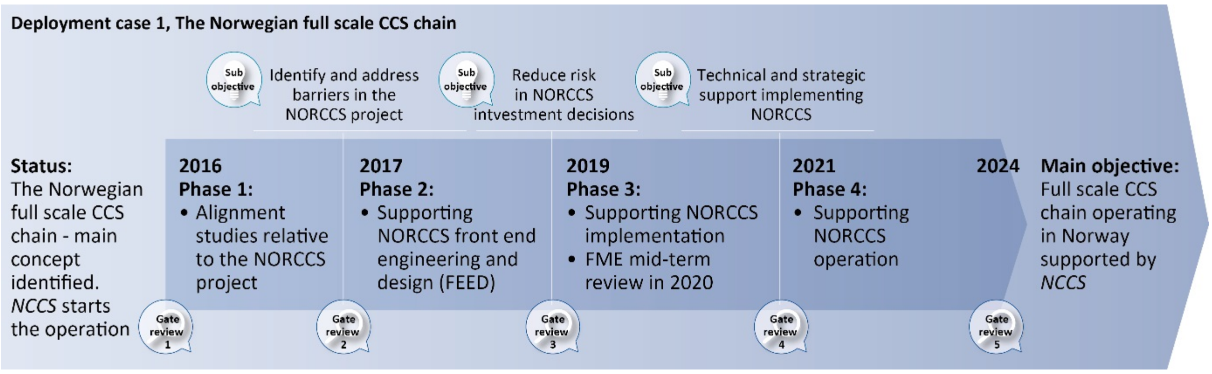
- To be a CCS research hub benefitting from close cooperation between highly ranked academic institutions in Europe and North America.
- Influence Europe's CCS strategies by participating in the development of the SET Plan, the Integrated Roadmap for CCS and working programs in Horizon 2020 as members of the ZEP Technology Platform and the European Energy Research Alliance (EERA) on CCS.
- Support and strengthen the memorandum of understanding (MoU) between the US DOE and the Norwegian Ministry of Petroleum and Energy on CCS research by offering to operate a secretariat for the MoU initiative.

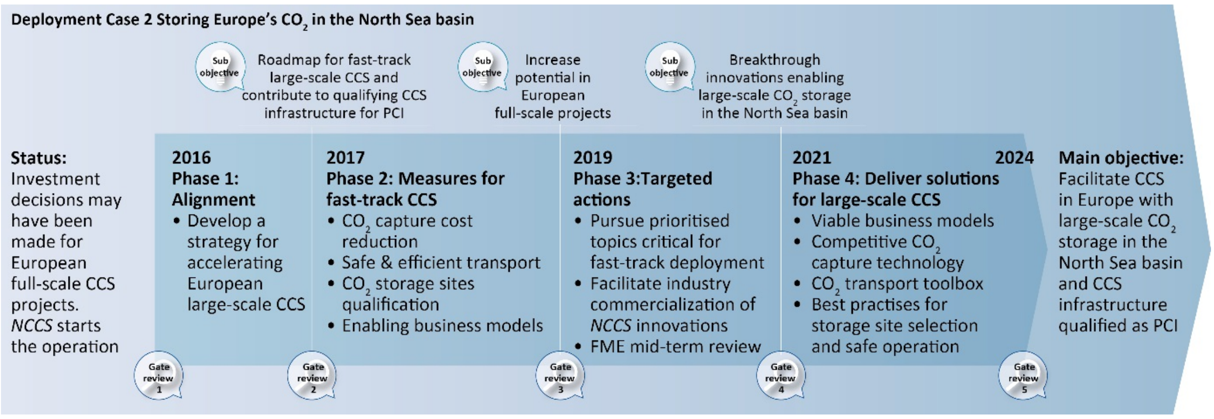
Research Plan and Strategy

Research Plan

NCCS will conduct high-quality strategic research in international networks of world-class experts, where the work of PhD candidates and postdocs is also fully integrated. The overall methodology will be the deployment-case orientation of NCCS, with CO_2 capture, transport and storage research aligned from a chain perspective. This will ensure e.g. that impurities in the CO_2 and fluctuations in the CO_2 stream over time are considered in a consistent manner for each deployment case.

NCCS will apply a dual approach with experimental and analytical research complementing one another. Research topics will require studies of both fundamental aspects (e.g. as CO_2 thermodynamics) as well as more applied research, (e.g. fiscal flow metering development).





Well-structured research plans, reviewed and revised during the DC Gate Reviews, will set the direction for what is required to advance technologies to a higher TRL.

Research will contribute to advancing TRL either directly in the more applied research tasks, or indirectly by supplying fundamental insights and mathematical models to other tasks along the deployment case chain. This will allow quantification, and thus give increased confidence and safety, and reduced cost. Data and knowledge from industry (e.g. Aker, Norcem and Krohne) and the Boundary Dam full-scale project will also play a key role in increasing understanding and advancing TRL.

This broad scientific approach, involving all key elements of the CCS chain, requires a consider-able budget for NCCS to be able to significantly contribute to fast-track deployment of CCS in Norway and Europe. To generate the new knowledge required to overcome the barriers against CCS, a number of carefully chosen PhD topics is included (Table 3). This is the rationale for applying for the maximum available funds from RCN 30 MNOK per year for 8 years.

Innovation Strategy

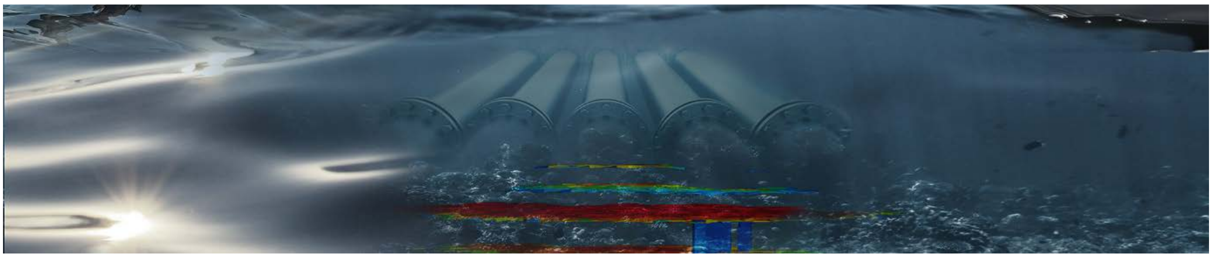
The NCCS industry-driven case-oriented concept has been developed with industry partners, ensuring strong industry ownership and governance of the Centre. The scientific tasks will be assessed and reviewed according to the phase-gating model. This is a well-tested and developed model used in numerous innovative companies and processes. The industry partners will have an active and key role in decisions at each phase gate.

As an international CCS research hub, NCCS is built to promote open innovation processes [10]: companies involved in the Centre will be able to commercialize ideas and emerging technology from outside their company boarders, building on others' ideas and even bringing ideas from NCCS into new and emerging markets. This model optimizes innovation and technology output across company boarders and increases the potential gain for each company involved, as the pool of ideas and concepts emerging from NCCS will be larger than that of each company.

Innovation may be defined as a product, a technology, a component, a process, a model, a concept, an experimental facility or a service that is new or significantly improved with respect to properties, technical specifications or ease of use. This gives many potential routes for commercialization – from a single actor, via joint venture, to broad implementation for several stakeholders or markets. Thus, commercialization following the open innovation model requires a comprehensive intellectual properties (IP) strategy in order to maximize value creation for each involved company.

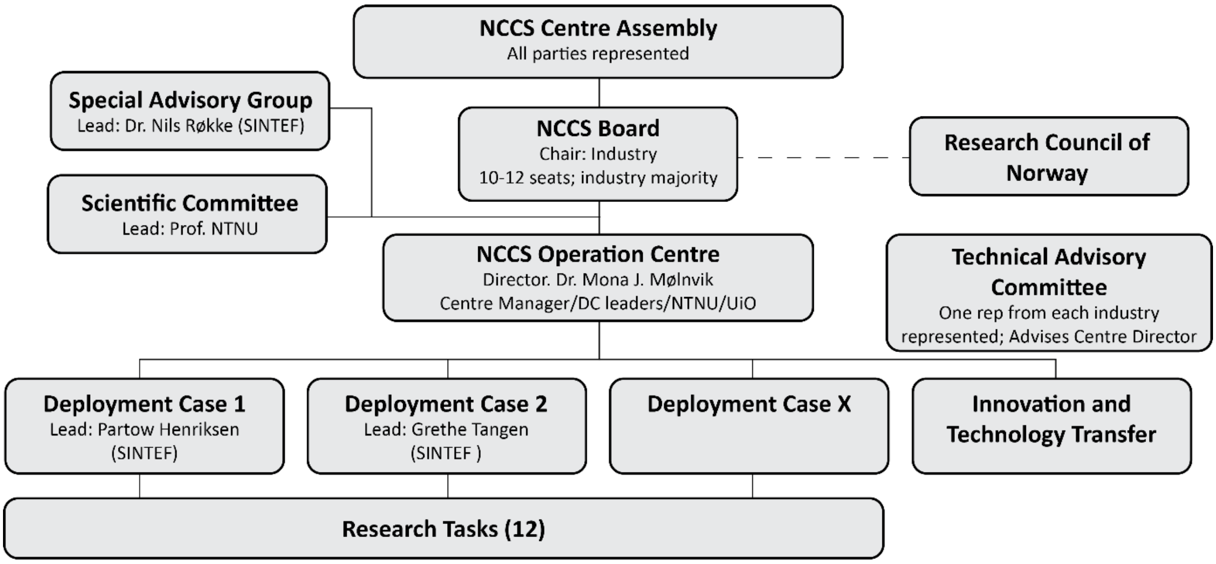
Therefore, NCCS will aim to disseminate results among partners whenever possible and at the same time secure IP rights for each partner where necessary.

In order to increase this innovative mind-set among researchers and partners, initiatives such as annual Innovation Camps and a dedicated NCCS Innovation Award will also be established. Innovation Norway and the CLIMIT Demo programme organized by Gassnova will be central partners in pursuing innovation opportunities beyond what is currently described in NCCS.



Organisation

Organizational Structure



Partners

Research partners

British Geological Survey	Norges Geotekniske Institutt	Norwegian University of Science and Technology	Ruhr – Universität Bochum
SINTEF Energy Research	SINTEF	SINTEF Industry	TNO
Technische Universität Munchen	The University Centre in Svalbard	University of Zürich	University of Oslo

Industry and vendor partners			
Statoil	Gassco	Shell Global Solutions International B.V.	Total
Norsk Olje og Gass	Aker Solutions	Ansaldo	CoorsTek
GE Power	Quad Geometrics	Larvik Shipping	Krohne
NORCEM	Oslo Kommune, gjenvinningsetaten		

Associated partners			
ECCSEL	US Department of Energy	UKCCS	Scottish Carbon Capture & Storage
Lawrence Livermore National Laboratory	Sandia	Massachusetts Institute of Technology	

Cooperation between partners

As an industry-led center in the start-up phase, great effort has been made to create good arenas and processes for cooperation with industry partners. An important and highly successful measure is establishing "families" in each task. The Task families include specialists from industry and research actors with particular interest in topics addressed. Through workshops and Skype meetings, all partners are able to contribute to technical discussions and affect ambition for next year's work program. NCCS includes a number of industry companies and most have been active contributors in one or more task families.

NCCS aims to be a dynamic center addressing challenges of high relevance to industry. An important tool for this is the Technical Advisory Committee *(TAC)*, which was established in 2017. The committee consists of and is led by industry, and the purpose is to advise the Center Director on strategic choices of direction and prioritization of topics in the portfolio of research activities. The committee has regular meetings, two in 2017. Mr. Arve Erga (TOTAL) is the leader of the TAC.

The task *Innovation and Technology Transfer* has a special responsibility for ensuring continuous focus on value creation potential and facilitating processes that promote innovation. In 2017, a workshop with user partners was held to establish appropriate strategies for IP (Intellectual Property) management. The work continues in 2018. In addition, NCCS collaborates closely with its partners on how industry addresses innovation and innovation processes. The task also held a webinar in 2017 "NCCS Webinar on Innovation in FMEs.

The annual NCCS Consortium Days is a central meeting place for the centre partners. In November 2017, the first two-day gathering was organized with presentations by industry partners, research communities and funding initiatives "NCCS Consortium Days 2017: Lessons learned from the Norwegian Full-Scale Project, CCS legal requirements, hydrogen and more..". In addition, poster sessions were set up where user partners could meet representatives from all the work packages and get presented results from the first year.

Participants at the NCCS Consortium Days 2017

Webinars have proven an effective and popular way to reach partners. NCCS held its first three webinars during 2017, one on innovation and two dedicated to planning of deployment cases. The strategy for 2018 is that each research task will conduct at least one webinar each where results are presented and discussed.

In autumn 2017, the center management took the initiative to meet all key actors in the Norwegian Full-scale project, i.e. the responsible for capture, transport and storage activities, as well as Gassnova as project owner. NCCS wishes to be a resource for the project and the purpose of the meetings was to ensure a good understanding of industry challenges and ensure that NCCS research is complementary and relevant to the companies. The plan is to continue this important dialogue.

Research Activities and Results

Research in NCCS addresses challenges critical to realization of two different CCS scenarios, or Deployment Cases (DC): *CCS for Norwegian Industry*, and *Storage of Europe's CO_2 in the North Sea*. The work is organized in 12 work packages, or tasks, that together cover the entire CCS value chain. An extra task, serving all the 12 research tasks, is established on *Innovation and Technology Transfer*.

NCCS includes a comprehensive education program with fellows integrated into the Center's research tasks and many of the activities use laboratories established as part of ECCSEL, a distributed research infrastructure for CO_2 handling.

By 2017, all the work packages are well established and highlights are already many. Most work packages in NCCS address issues relevant to both DC scenarios. The following pages present highlights from 2017.

Selected Cases

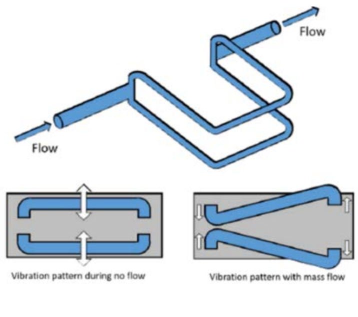
Why Investigate Fiscal Metering of CO_2?

Fiscal Metering is the measurement of a quantity of product involved in a commercial transaction. The EU ETS (Directive 2003/87/EC) creates the commercial environment for fiscal metering of CO_2 and defines the maximum uncertainty in the measurement and delivery of CO_2. The use of fiscal meters eases the burden on users when calculating uncertainty but to our knowledge, no metering technology has been verified with CO_2 at the accuracy required by the ETS at full-scale flow rates.

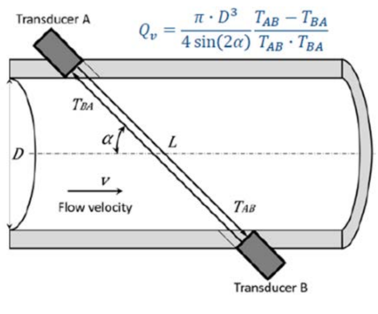
Finding solutions for fiscal metering is central for both Deployment Cases in NCCS. For instance, in DC2 – *Storing Europe's CO_2 in the North Sea*, we need flow metering at an accuracy equal to the specifications of the EU Emissions Trading System regulations to avoid purchasing emission allowances. In addition, we need accurate metering for transactions between the storage and CO_2 source operators who most likely have different owners. Likewise, the *Norwegian full-scale CCS project* will be subject to CO_2 regulations and incentives, and there will be a change of CO_2 ownership between source and sink. The fiscal metering activity in NCCS will provide valuable support for the development of DC1 – *CCS for Norwegian Industry.* Finally, the objectives of the activity are in line with the overall innovation objective of the center. KROHNE is a world-leading manufacturer and supplier of solutions in industrial process instrumentation and is crucial to the success of this research activity. As a producer of both ultrasonic and Coriolis meters, Krohne will be in a position of answering many of the current gaps listed above, and may point in the right direction on others.

Results and Achievements 2017

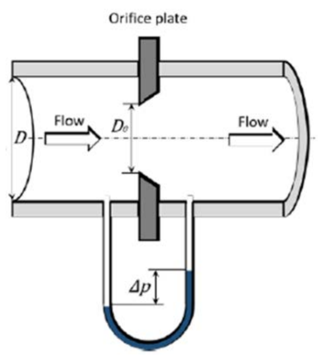
The specifications for fiscal metering have been proposed for relevant interfaces in the Deployment Cases such as ship transfer, onboard metering, and pipeline fiscal metering. This is available in a memo, *NCCS specifications and preliminary survey of available technologies for fiscal metering*, where four metering technologies were assessed, with input from KROHNE. It was recommended to continue working on ultrasonic and Coriolis meters, and include an assessment of orifice plates.
A feasibility study for a high-pressure CO_2 technology test center has recently been granted by the CLIMIT Demo program to verify fiscal flow meters at industrial relevant scale. If realized, this test center will test, verify, and assist in the development of various flow metering technologies at industrially relevant scales. The work in NCCS will help setting the specifications of the test center such that it in the most efficient manner reduces current knowledge gaps regarding CCS flow metering. This feasibility study has some of the same partners as NCCS and the two projects will complement each other. The experiments that may be performed at the planned test center will greatly aid the task's overall goal of raising the TRLs of fiscal metering technologies for CCS.



Coriolis Principle



Ultrasonic meter



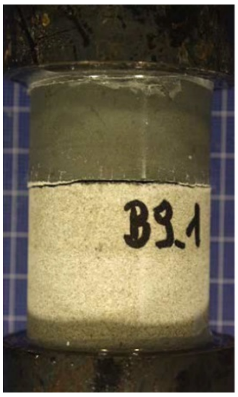
Orifice meter

Sement-til-stein-hefting

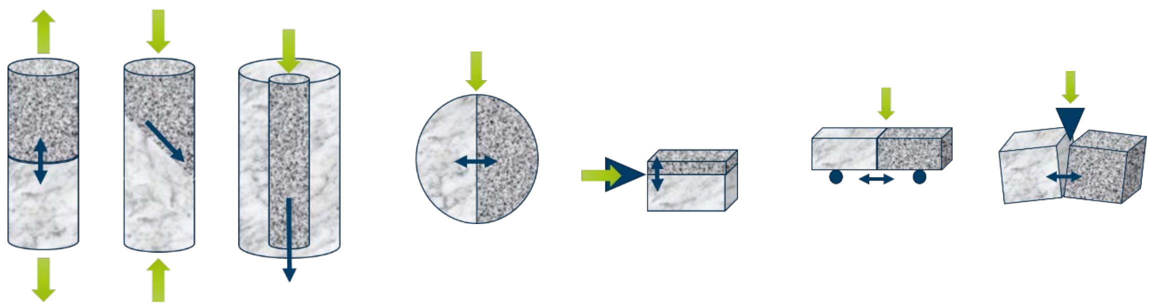
When drilling wells for oil and gas production or CO_2 injection for storage purposes, one must ensure that metal piping systems like liquids are pumped through held in place. Here cement is important as a binder between steel production pipes (called feed pipes in the oil and gas industry) and rock formation that the well is drilled through. To qualify cementing, engineers must ensure good cement placement, strong adhesion and durable insulation of the well from the environment. This is essential to avoid unwanted leaks back to the surface. In NCCS, SINTEF has carried out laboratory tests to investigate cement strength as a function of chemical composition, exposure to CO_2 and typical conditions in the subsoil. SINTEF has also adapted and proposed new methods to try to measure cementing to stone rocking. This is not trivial, since it is about breaking a break just in the transition between stone and cement.

Staple strength comes in several varieties: shear strength, tensile strength and what is called hydraulic staple strength. Cutting adhesion must be tested so that the cement glides off the stone substrate in a controllable manner; In the same way, tensile adhesion must be tested for breakage where this time no sliding underneath the shear occurs. Hydraulic staple testing involves measuring for which fluid pressure on one side of the stone / cement plug an increase in pressure on the other side is noted. It becomes like a signature on fluid communication and therefore fracture fractures (either in cutting or tension mode).

In 2017, test results from several SINTEF departments in BIGCCS and other projects were summarized in a report describing what is measured by each method. By 2018, NCCS will establish reproducible testing methods to provide industry partners with sought-after input values for simulation tools and optimization of cement composition.



Breach between stone and cement after a stretch test.



The different tests that have been performed at SINTEF, and which will be standardized in NCCS.

Why quantitative monitoring is important for cost-efficient CO_2 storage

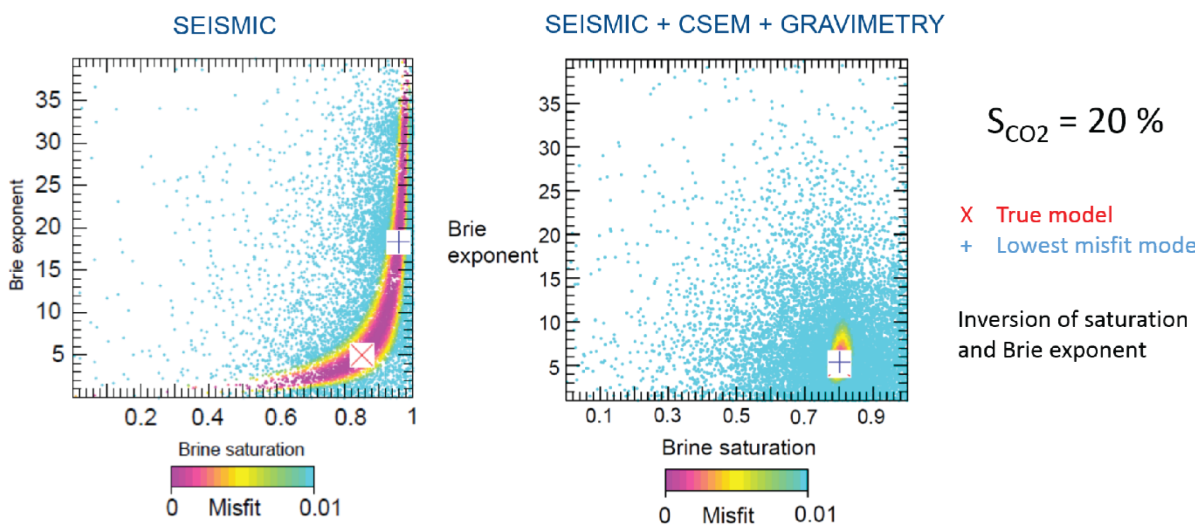
Implementation of large-scale CCS is currently mainly limited by cost aspects. The storage and monitoring are parts of the value chain where significant cost reduction is desired. However, the geological reservoir and seal are difficult to characterize and uncertainties may be large. In addition, monitoring, verification and accounting (MVA) of CO_2 storage are legal requirements meant to ensure containment and conformance during the injection and after the site is closed.

Therefore, monitoring techniques, mainly based on 3D seismic surveys, are necessary, but expensive, and can require extensive processing. Task 12 in NCCS focuses on how to optimize the monitoring techniques to find the best compromise between cost, resolution and sensitivity in order to fulfil the MVA regulations at a minimal cost. Estimation of quantitative properties such as CO_2 saturation and pressure is vital to ensure containment and conformance, while combining different monitoring techniques in a smart way will allow minimization of monitoring costs.

Quantitative monitoring for estimation of CO_2 saturation

The workflow developed by SINTEF researchers to estimate these properties have been first applied to Sleipner data. Sleipner is the world's first CO_2 injection site in the North Sea and extensive monitoring surveys have been carried out since the start of the injection in 1996.

The different vintages of seismic surveys have shown a clear signature of the injected CO_2 in the sandstone reservoir. Using conventional seismic processing techniques allow to follow the spatial migration of the CO_2 plume. However, the quantification of CO_2 saturation and pressure requires advanced imaging techniques. At SINTEF, a two-step approach is used, first deriving high resolution maps of geophysical properties, and then, a second inversion step calculating the properties of interest such as porosity, CO_2 saturation or pore pressure. The advantage of this approach is that the assessment of uncertainty can be integrated the uncertainties propagated until the final result.



Synthetic example of how well Sleipner rock physics/reservoir parameters can be constrained using seismic data alone (left) or a combination of seismic, CSEM, and gravity data (right). The images clearly show how much closer the parameter estimation (lowest misfit model) is to the true value (true model) when using a combination of input data. For cost-efficient monitoring, this added accuracy has to be weighed against the added costs of acquiring more data. This calls for a careful value-of-information assessment, which is an important part of the NCCS Task 12 work plan.

The method provides an estimate of CO_2 saturation in the whole reservoir. At Sleipner, in the Utsira sandstone, the CO_2 is migrating upwards by buoyancy to the upper seal of the Nordland shales. Inside the reservoir, thin layers of shale are blocking the migration upwards and accumulations of CO_2 under these thin layers are easily observable in the seismic images. The quantification of CO_2 saturation gives values up to 90% of CO_2. The rest of the porous medium is filled with brine, the original fluid present before CO_2 injection. The pore pressure estimation is not relevant at Sleipner as the aquifer where the CO_2 is injected is very large and the pressure build-up is negligible.

Value of information and choice of monitoring techniques

In addition to seismic surveys, other monitoring techniques, such as electromagnetic and gravity-based methods could be used for CO_2 storage monitoring. These techniques usually have lower resolution but are very sensitive to fluid resistivity and density changes and could therefore be a good alternative to map CO_2 migration and saturation. Currently, work is carried out by SINTEF researchers to combine these methods and seismic methods into the same quantitative workflow. This will constrain the monitoring results more and will reduce uncertainties in the obtained estimates.

The costs related to the different techniques are quite different, and even if seismic surveys are required to get good enough spatial resolution, gravity and electromagnetic surveys may be used in addition to allow less frequent seismic surveys. Using an advanced workflow based on the value of information concept will help to determine which techniques should be used with which time interval. Finding a clever way to quantify the value of information is crucial for discrimination between methods and optimization of the monitoring plan.

Summary

Quantitative monitoring techniques are required for proper conformance and containment verification, and in this context uncertainty should also be taken into account. The two-step workflow developed at SINTEF provides an efficient and flexible way of combining different monitoring techniques to achieve quantitative estimates of properties such as porosity, CO_2 saturation and pore pressure. Furthermore, using the value of information concept will help to find a better compromise between cost, resolution and sensitivity of the different techniques and ultimately to optimize the monitoring plan.

Tailor-made molecules for increased CO_2-EOR efficiency

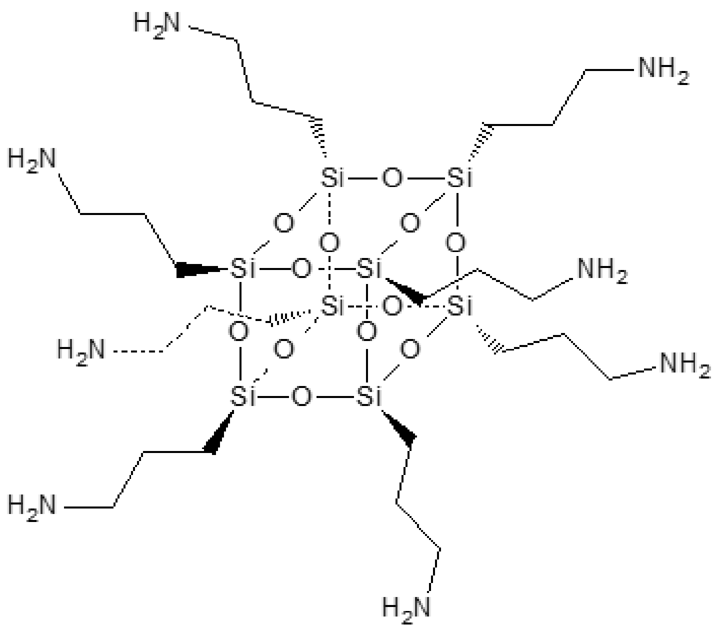
Injection of CO_2 into oil fields can increase the amount of oil produced (CO_2-EOR), while at the same time storing large amounts of CO_2. This is the only currently available method to significantly reduce the overall cost of a CCS chain. CO_2-EOR has been in use for several decades at onshore fields in North America. The density difference between CO_2 and oil leads to gravity segregation and reduced efficiency. The lower viscosity of CO_2 also contributes to reduced efficiency, since the gas will tend to bypass the oil. Onshore, the relatively low cost of drilling new wells makes short well distances possible. This reduces the overall impact of gravity segregation. Offshore, like on the Norwegian Continental Shelf, the cost of wells is much higher, and the well distance therefore tends to be much larger than onshore. Something else is therefore needed in order to increase the efficiency of CO_2-EOR.

Slowing down CO_2

The density of CO_2 at reservoir conditions is already quite high compared to other substances that are gaseous at surface conditions. Much research effort has therefore been focused on methods that can slow down the CO_2, such as generation of foam or increasing its viscosity. It is also desirable to find substances that can be carried by the CO_2 deep into the reservoir, since this would improve the efficiency. Several chemicals have been found that can do this, but unfortunately these are either too expensive or unacceptable from an environmental viewpoint.

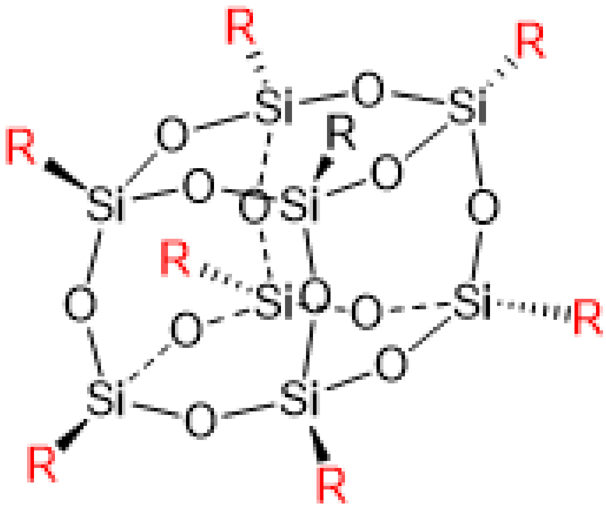
Designer materials

Enter nanotechnology. With the advent of this technology came methods for creation of new hybrid materials. The FunzioNano® technology developed at SINTEF can be used to graft hand-picked active molecular groups on to nano-sized inorganic cores. The result is tailor-made hybrid molecules that can have complex functionalities. In NCCS this technology will be employed to try to create novel materials that will stabilize CO_2-water foam and thereby can slow down the CO_2 and increase oil production efficiency.



A basic starting form of the nanomaterials that SINTEF's group in Oslo is working with; an inorganic core with multiple amine branches.

The first few test batches of hybrid materials have been synthesized in SINTEF's laboratories in Oslo, and are currently being tested in the SINTEF's Reservoir Technology laboratory in Trondheim. The testing will guide the selection of molecular groups for the next batches of materials.
Open research questions

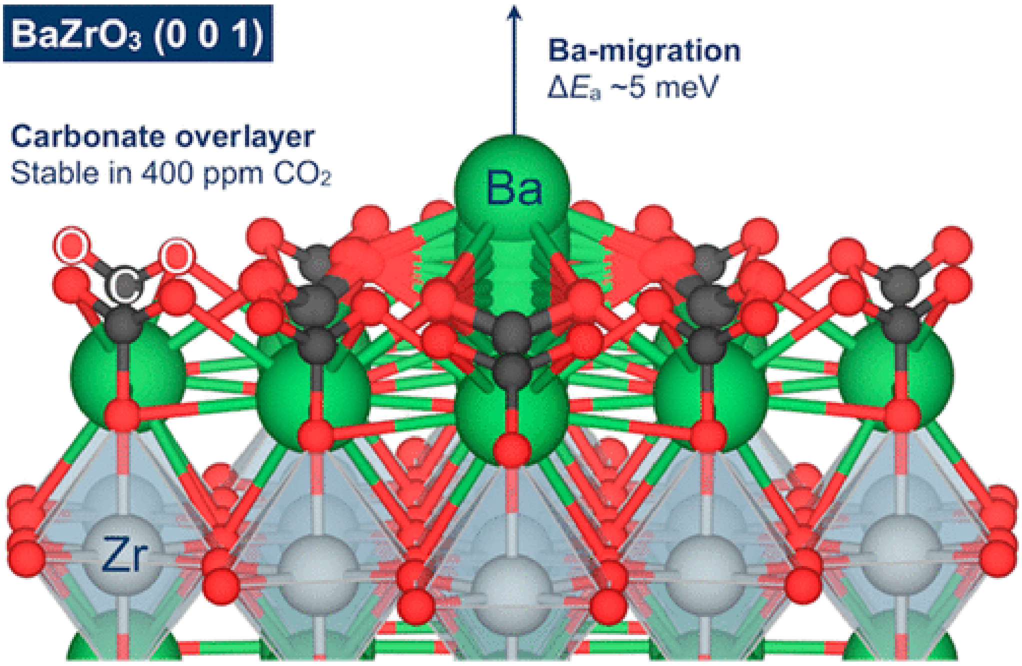


The trick in making efficient EOR chemicals is to identify replacement branches with functional groups (R) with the desired properties.

There are still many open research questions, such as picking the right molecular groups for the desired functionality, development and testing of synthetization methods, properties in laboratory tests and at field scale, and the cost of manufacturing and deployment of such new materials. In NCCS we hope to answer some of these, and thereby possibly enable the next generation of CO_2-EOR.

Fruitful research visit to MIT related to low emission H_2 production

SINTEF Industry recently published a study on the interaction between CO_2 molecules and the surface of $BaZrO_3$ – a membrane material utilized in electrochemical membrane reactors for hydrogen production from natural gas in NCCS Task 3: Low Emission H_2 production. The Protonic Membrane Reformer (PMR) is a pre-combustion CCS technology being developed by NCCS partner Coorstek Membrane Sciences, and will be important in realising both deployment cases.



$BaZrO_3$

The study was performed in collaboration with the Tuller and Yildiz groups at Massachusetts Institute of Technology (MIT) through a research visit by Task 3 researcher Jonathan Polfus. The 6-month stay in the Boston area was supported by the CLIMIT program and the work on the fundamental understanding of the $BaZrO_3$-based membrane surfaces was also supported by the FOXCET project under the Nano2021 program.

Tuller group

The simulations at atomic scale showed a strong interaction between CO_2 and $BaZrO_3$ by formation of carbonate species on the surface. This may indicate a degradation process in which the membrane material reacts to barium carbonate, $BaCO_3$. However, further work shows that the presence of steam makes the reaction significantly less prominent. The potential degradation phenomenon therefore does not seem to be critical under the steam methane reforming conditions of the PMR, where the membrane is exposed to both steam and CO_2 at around 800 °C. This is in agreement with experimental results indicating no degradation when exposed to such conditions for more than 500 hours. Long-term tests are being performed in NCCS Task 3 to further confirm the performance and stability of the PMR reactor under operating conditions.

Yildiz group

Bikes, gravel and CO_2 flow out of equilibrium

The purpose of NCCS Task 7 is to improve and expand our knowledge on the design and operation of safe and efficient CO_2-transport systems. Part of this is to understand CO_2 flows that are out of equilibrium.

I'll try to give a flavour of what we mean by non-equilibrium here: Two quantities in non-equilibrium, if left alone for a while, will tend to approach each other. Also, two quantities in equilibrium can get into non-equilibrium if conditions change.

Bike example

Many of you have experienced an example of the latter while happily riding your bike on an asphalt road, and suddenly finding yourself in a curve with gravel on top of the asphalt. The gravel changes the maximum transversal force the bike wheels can transmit to the ground, so that the bike starts moving sideways. The new equilibrium state is you and the bike lying on the ground – hopefully without too many scratches.

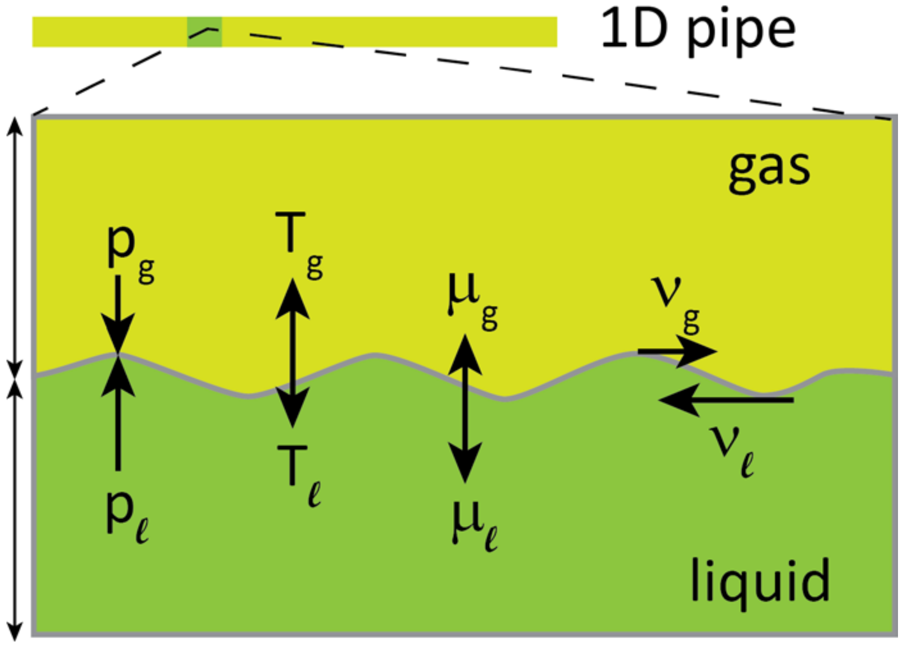
Child and bik aving found a new equilibrium state. Photo: Shutterstock

Models

In Task 7 we are not concerned with bikes, but with slightly analogous dynamic situations which we need to model. A model in this context is a more or less simplified view of a part of the physical world, along with mathematical expressions describing this view. We need experiments to assign values to coefficients appearing in the equations. Conversely, the equations help us set up the relevant experiments.

Ship transport
Ships are seen to be an efficient way of transporting CO_2, especially for long distances or when flexibility is needed. One design question is at what pressure (and temperature) the CO_2 should be in while in transit.

A relatively low pressure of about 6–7 bar is generally seen as efficient, but this is close to the state where solid CO_2 (dry ice) is formed. One does not want solid CO_2 to block e.g. valves and pipes. Here the non-equilibrium comes in. We need to know under which conditions solid CO_2 is formed, and how much. Once it's there, we need to know under which conditions the solid CO_2 sublimes (turns into gas) or melts, and how fast.



A flow can be out of equilibrium in pressure (p), temperature (T), chemical potential (μ) and velocity (v). Illustration: Gaute Linga

Pipeline transport
If somehow a hole is formed in a CO_2-transport pipeline, it is important that it does not develop into a long running-ductile fracture. See our previous blog (Safe CO_2 transport pipes is part of the climate solution) for more information on this subject.

In order to design pipelines, we would like to be able to describe the fast physics involved during a running-ductile fracture. It all happens within some tens of milliseconds. This may not be long enough that the fluid can be thought to be in equilibrium. Here we need to consider the liquid and the gas phase that both will be present during a depressurization.

The two phases can be out of equilibrium in several ways. They may have different pressures, temperatures, chemical potentials and velocities, see the above figure. We have the hypothesis that if we account for these phenomena, then we will also be able to describe the running-ductile fracture more accurately, which in turn will enable us to design and operate pipelines with greater confidence, and also to evaluate the use of existing hydrocarbon pipelines for CO_2.

PhD project

As one may imagine, bringing non-equilibrium into the fluid flow models increases the complexity. This is the price to pay for better accuracy and robustness. Task 7 will study several aspects related to non-equilibrium flow of CO_2. In particular, one PhD will be educated on the subject, in a collaboration between NTNU and SINTEF. The PhD candidate, yet to be recruited, will enlighten the subject both from the modelling and the experimental side. Depressurization experiments will be performed in the ECCSEL depressurization facility, which is currently under construction at the roof of the NTNU-SINTEF Thermal Engineering Laboratories.

In this work, we will span the gap from experimental observation and mathematical description of physical phenomena, to industrial applications. This is a way of reducing CCS-project risks and therefore accelerating CCS deployment.

Results from NCCS tasks

The CO_2 value chain and legal aspects (Task 1)

The task seeks to demonstrate the importance of CCS to decarbonize the energy and industrial sector to reach the Paris Agreement target. It will provide recommendations on the best measures to cut CCS costs and assess shortcomings in the current legal framework applicable to CCS operations at national and international levels. This will help enable a faster and cheaper deployment of CCS technology.

www.sintef.no/NCCST1

Results 2017
One of the critical activities in 2017 was to provide benchmarking reference points to evaluate the impact of new knowledge resulting from other centre activities, as well as the potential of activities of interest.

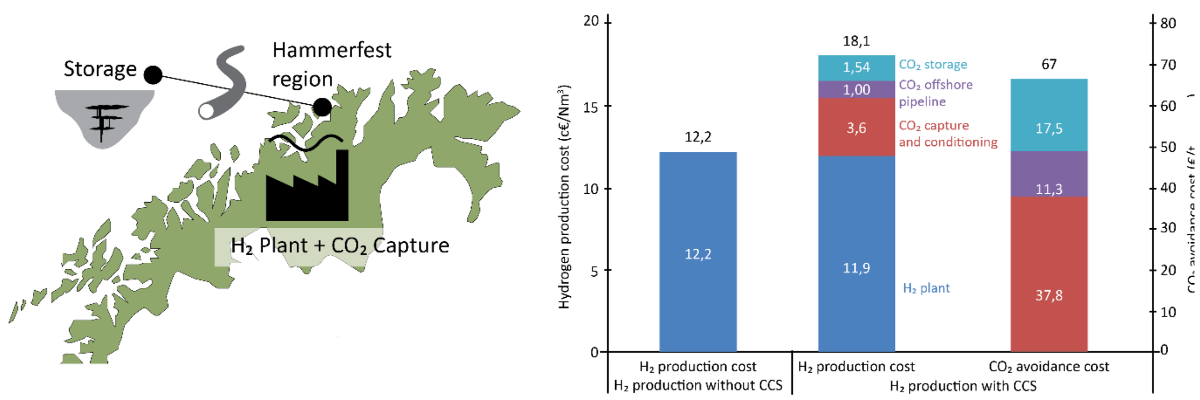
Two reference CCS chains were selected and defined in discussions with partners, assessed and evaluated in collaboration with Task 6:

- CCS from a natural gas combined cycle (NGCC) power plant
- CCS from a hydrogen production plant

The obtained results show that the CO_2 capture and conditioning cost is the main contributor to the CCS cost (57-70%), while the transport and storage costs account for 16-17% and 18-26% of the chain cost. Equally important, the semi-detailed cost breakdown was presented to provide a deeper understanding of the key contributors to the cost of the whole chain, and therefore to identify points, which if reduced, could have the most impact.

The results of the assessment of these reference chains are expected to be used by task leaders, Centre management, and industrial partners to:

- Follow the impact of different performed activities throughout the Centre
- Support the prioritization of existing and new activities in the Centre
- Assess how the Centre has performed in terms of reaching its ambitions



(a) Illustration of considered infrastructure geographical locations for the reference chain for hydrogen production with CCS (b) Overall breakdowns of H_2 production cost and CO_2 avoidance cost of the reference chain for H_2 production plant with and without CCS

Solvent technology – environmental issues (Task 2)

The task works to understand degrading of solvents better by investigating which factors has the highest impact on the stability of amines (organic compound derived from ammonia). Furthermore, the task will contribute to reduction of operational- and investment cost by indicating amines with higher stability and developing technologies to control and monitor solvent stability.

www.sintef.no/NCCST2

Results 2017

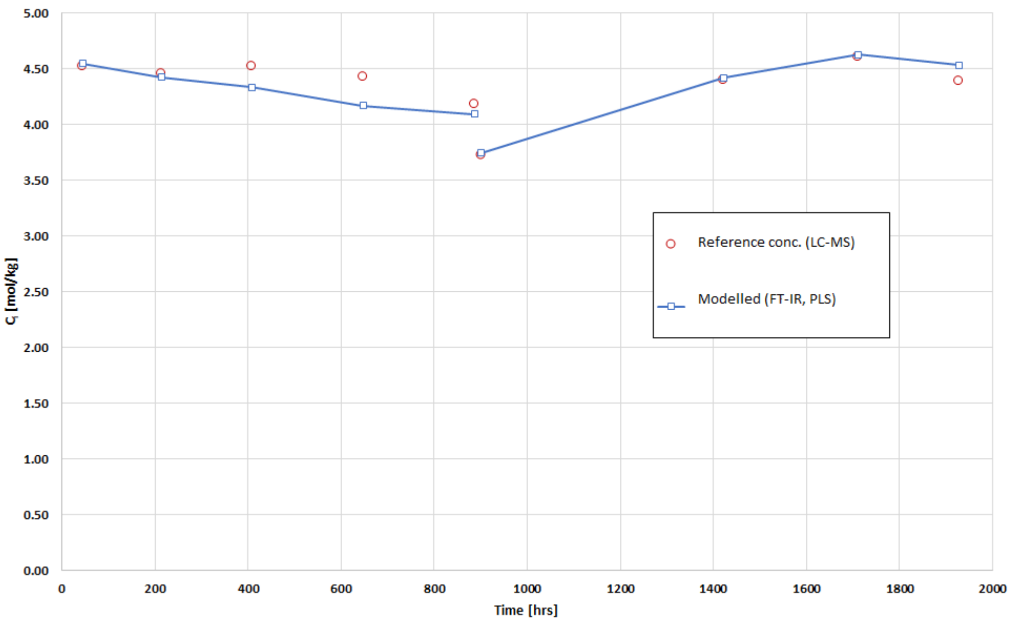
One of the drawbacks for post-combustion CO_2 capture with solvent technology is that absorption capacity of a solvent is reduced because of for example degradation. This mean that unwanted chemical reactions (degradation) occur in addition to the CO_2 absorption and desorption reaction.

Different strategies are used to reduce unwanted reactions:

- Development of mitigation technologies to reduce degradation
- Development of new experimental methodologies to predict chemicals stability of new solvents at process conditions
- Gathering of knowledge on relation between amine structure and chemical stability. In addition, online monitoring of the solvent status in the process has been a focus.

The main results from 2017:

- Successful proof-of-principle of the oxygen removal concept (mitigation technology)
- New methodology has been suggested for evaluation of chemical stability of solvents
- Several amine structures sensitive to degradation have been identified
- The existing Partial Least Square (PLS) model used to evaluate solvent status has been improved.



Comparison of different models developed for prediction of CO_2 concentration in solvent (Reference Conc – samples from a pilot test campaign at Tiller CO2Lab)

Low emission H_2 production (Task 3)

The current efficiency level of the H_2 production is around 60-70%. The goal of the task is to develop hydrogen production technology with an efficiency higher than 75% including capture of CO_2 to lower emissions from the H_2 industry.

www.sintef.no/NCCST3

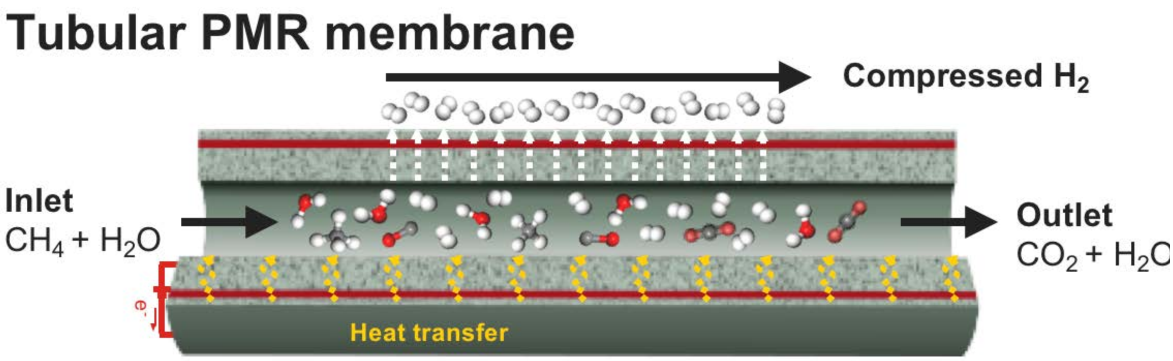
Results 2017

The task deals with development of the Protonic Membrane Reformer (PMR) technology by CoorsTek Membrane Sciences which allows hydrogen production with CO_2 capture in a modular steam methane reformer.

The work aims to identify and improve material stability and performance issues of the ceramic membrane and seals under PMR operating conditions and thermal cycling.

A membrane unit at SINTEF was upgraded for testing of electrochemical membranes provided by CoorsTek and commissioned for PMR test conditions (800 °C and 10 bar pressure with a steam to carbon ratio of 2.5). A single-segment tubular membrane was tested under PMR conditions and further improvements were made to the setup.

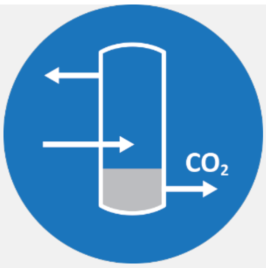
A paper was submitted on atomistic studies of CO_2 adsorption on the $BaZrO_3$-based membrane material in connection with a research visit at MIT supported by CLIMIT and other RCN projects.



Single tubular segment of the protonic membrane reformer for production of compressed H_2 by steam-reforming and water-gas shift. Scanning electron micrographs show close of the membrane electrolyte and electrodes. Figure from Malerød-Fjeld et al. Nature Energy (2017) https://doi.org/10.1038/s41560-017-0029-4

CO_2 capture and transport conditioning through liquefaction (Task 4)

The task is looking to use liquefaction to optimise the transport condition of CO_2, thus making liquification a mandatory processing stage in the interface between capture and transport. To do this, an efficient CO_2 liquefier process will be derived. Important criteria are energy- and cost efficiency adhering to transport specifications and safety.



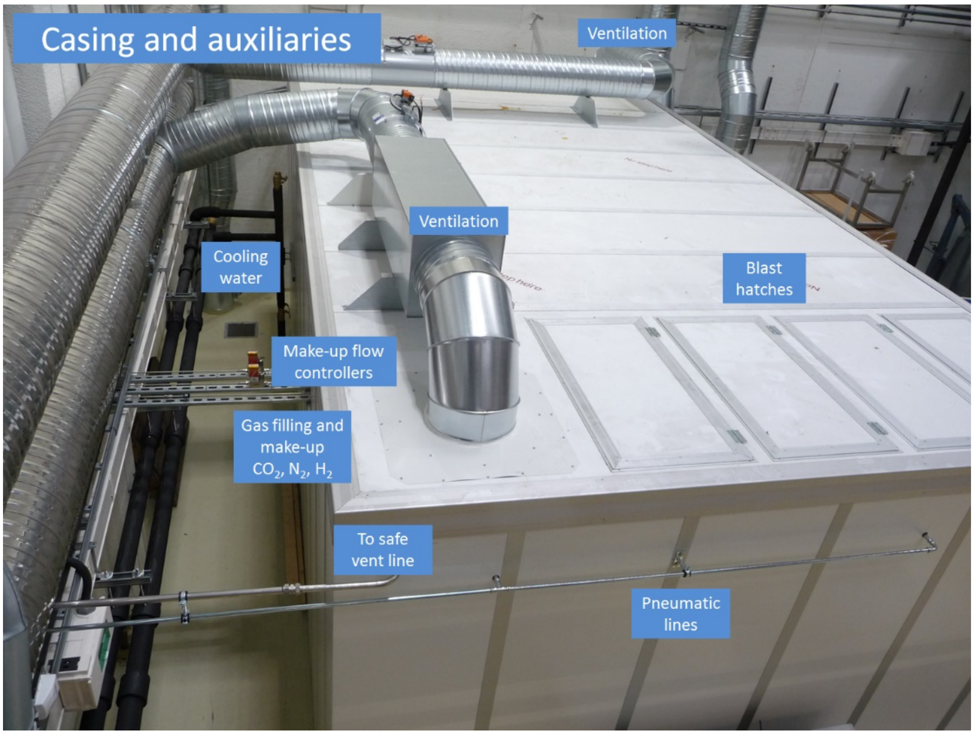
www.sintef.no/NCCST4

Results 2017

The main activity was to provide an overview of the relevant inlet and outlet boundary conditions and specifications (compositions, temperature, pressure etc.) to which CO_2 liquefaction processes must adhere. The gathering of information was done by data collection from other deliverables where available, as well as by communication with other NCCS tasks.

Examples of inlet boundary specifications are: CO_2 captured from post-combustion capture with relatively high purity, and CO_2-enriched synthesis gas retentate from protonic membrane reforming (PMR). Outlet specifications are mainly high-pressure CO_2 for pipeline transport and liquid CO_2 for ship transport. Low-temperature CO_2 processing and its adherence to the various boundary conditions in post- and pre-combustion applications was given an initial consideration.

In parallel with the NCCS work, the task core group is involved in the construction and commissioning of a laboratory pilot infrastructure for low-temperature CO_2 separation and liquefaction, funded through the ECCSEL infrastructure programme. The infrastructure has a capacity in the range 5–15 ton CO_2 per day, and can operate down to around -55°C temperature range and up to 120 bar pressure. Upon completion, the infrastructure will be available for experimental activities relevant for NCCS.



Housing of CO_2 liquefaction and separation experimental facility.

Gas turbines (Task 5)

Task 5 aims to enable deployment of carbon storage on the Norwegian continental shelf through O&G rigs, and throughout Europe with gas turbine engines. The overall objective is to assess the stability and operability of gas turbine combustion systems. Ultimately, the task will evaluate their impact on power generation, thermodynamic efficiency and pollutants emissions.

www.sintef.no/NCCST5

Results 2017

The research activities started in mid-2017 at SINTEF and focused on two modelling topics:

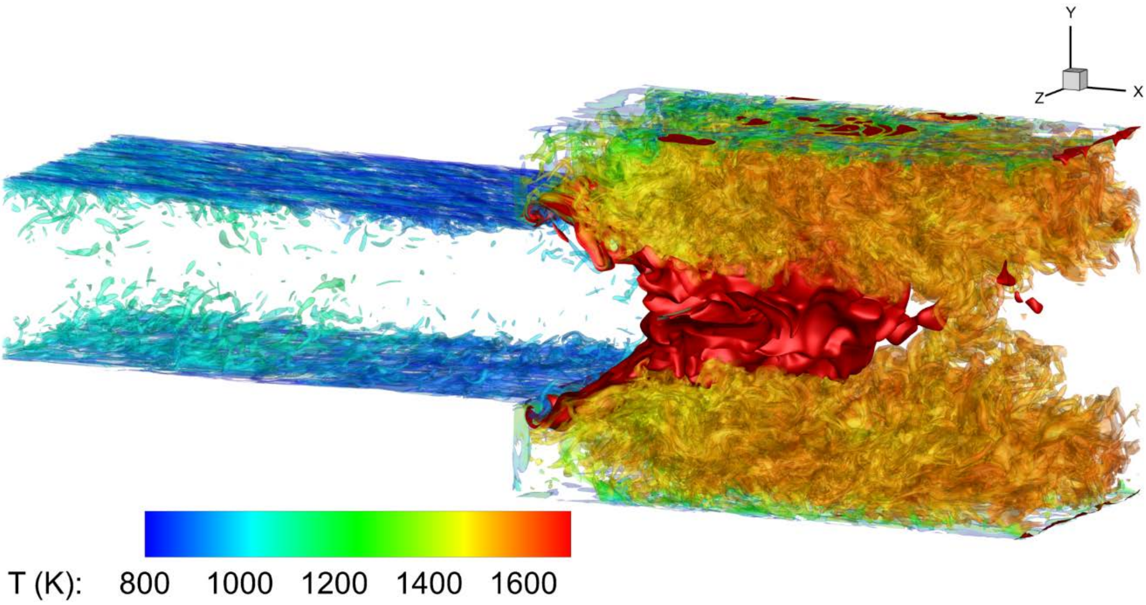
- High-definition numerical modelling of the reactive flow in Ansaldo's reheat combustion chamber
- Tuning of the chemical kinetics model to efficiently represent combustion at reheat conditions.

The technical work on both topics was planned and performed in close collaboration with Ansaldo's corporate combustor R&D group with frequent mutual visits between Trondheim and Baden (Switzerland) and with the University of California San Diego (developers of the chemical kinetics model).

Results obtained from the Direct Numerical Simulation (DNS) of a scaled, and geometrically simplified, version of the reheat combustor operating on the target hydrogen-air reactive mixture have provided the first detailed quantification of the combustion characteristics (flame propagation vs auto-ignition) in the device.

On the academic side, the work at NTNU has been mainly related to the preparation/commissioning of the experimental rigs and to the selection and set up of the academic positions (Postdoc/PhD).

Among NCCS industrial partners, Statoil is actively following the research with particular interest in the development of hydrogen-fired gas turbines, providing input and feedback.



Qualitative illustration of the turbulent reactive flow in Ansaldo's reheat combustion chamber. Turbulence structures are colored by the local fluid temperature, the flame is represented by the red surface.

CO_2 capture process integration (Task 6)

Task 6 investigates how to best integrate the capture process in the CCS value chain. A generic methodology for post-combustion CO_2 capture in waste to energy plants will be developed. The methodology will be used to redesign plants so they can support flexibility between heat (steam) and electricity output. The task will also develop a systematic approach to link solvent properties and cost reduction in end-of-pipe CO_2 capture.

www.sintef.no/NCCST6

Results 2017

Three main activities have been undertaken. One of these was to develop reference cases that would provide a benchmark to identify the potential of technologies developed during the course of NCCS.

Two reference CCS chains were selected and defined in discussions with partners, assessed and evaluated in collaboration with Task 1:

- CCS from a natural gas combined cycle (NGCC) power plant
- CCS from a hydrogen production plant

For the NGCC reference plant, the widely used European Benchmarking Task Force (EBTF) reference case was updated with an H class gas turbine. The overall NGCC plant efficiency with CO_2 capture was 54.5% compared to 49.5% in the EBTF reference case, and the efficiency penalty for CO_2 capture was 7.5 %-points compared to 8.6 %-points in the EBTF case.

Another activity was to develop an energy integration model to provide insight on how to integrate CO_2 capture to a waste-to-energy plant. The Klemetsrud plant will be used as a case study. A framework for energy optimization of the plant with CO_2 capture was established.

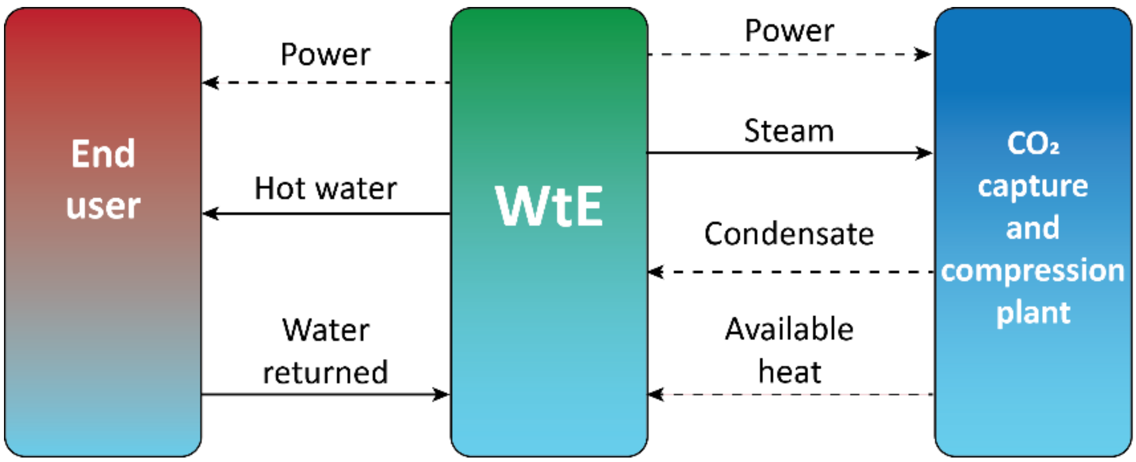


Illustration of energy flows in a waste-to-energy plant with CO_2 capture.

CO_2 transport (Task 7)

CO_2 transport has many hazards and uncertainties. Task 7 will provide knowledge to ensure safe and efficient CO_2 transport. E.g. running-ductile fractures in CO_2 pipelines, ship transport, impurities and non-equilibrium flow of CO_2 will be investigated.

www.sintef.no/NCCST7

Results 2017

The work focused on CO_2 transport by pipelines. We established a roadmap for the development of an engineering tool for fracture propagation control in CO_2-transport pipelines, which can help ensure safe and cost-efficient CO_2 transport. By engineering tool, we mean a tool that can be used with relative ease and with short runtimes by an engineer using a desktop computer, as opposed to heavier finite-element (FE) and computational fluid dynamics (CFD) simulations. The SINTEF coupled FE-CFD code is an essential part of the development, due to the physical insights that can be gained through its use.

Several publications have hypothesized that the CO_2 flow exiting the pipeline through a fracture is not in equilibrium. We made some progress in the modelling of non-equilibrium flow.

Work was also performed on the validation of our procedure for calibrating the material model in the FE-CFD code.

The NCCS industry partners, in particular Aker Solutions, Gassco, Larvik Shipping, Shell, Statoil and Total are following up and providing input to the work.

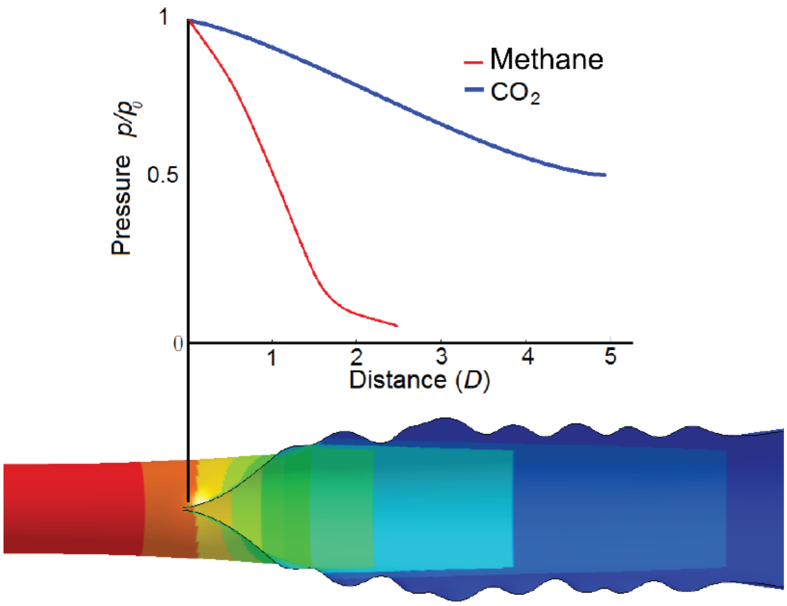


Illustration of the fact that CO_2 can exert a more severe load on an opening pipe than methane.

Fiscal metering and thermodynamics (Task 8)

Accurate thermophysical properties are needed for optimized design and operation of virtually all processes involved in CCS. This task aims to provide improved experimental data and models on properties of CO_2-rich fluids relevant for CCS, and facilitate fiscal metering of the same fluids.

www.sintef.no/NCCST8

Results 2017

"Fiscal metering and thermodynamics properties" has produced new experimental data fully characterizing the phase equilibrium on mixtures between carbon monoxide (CO) and CO_2 as a function of pressure at four different temperatures.

CO is an important impurity from many CO_2 sources and capture processes, and a better description of its impact is now possible.

The new data cover important knowledge gaps and are under publishing. Further, Task 8 has significantly improved the thermodynamic model description for many other types of mixtures.

A first assessment of potential technologies for fiscal metering of CO_2-rich flows has been performed, and specifications for fiscal meters for CCS have been proposed.

A new CLIMIT competence building project was granted for measurement and modelling of viscosity, density, and thermal conductivity. The project will be a part of NCCS ahead and apply new property correlations in reservoir simulations.

Extra HSE precautions are needed when working with CO.

Structural derisking (Task 9)

The main ambitions are to reduce risk related to injecting and storing CO_2 in the continental shelf, and contribute to maximize the CO_2 injection volume for the Smeaheia region (Norwegian Continental Shelf storage region) as well as develop techniques to address fault-sealing and integrity.

www.sintef.no/NCCST9

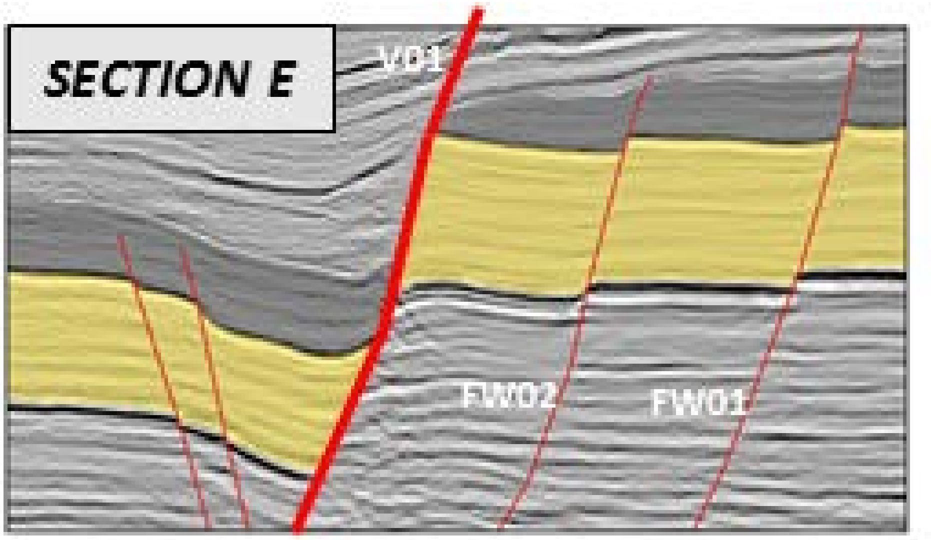
Results 2017

Main activities are related to establishing a good platform for collaboration between research partners, industry and the Northern Lights project.

The workshop in fall 2017 was an important arena for knowledge shearing and defining important research tasks related to fault seal and integrity evaluations for the Norwegian CCS project (NORCCS).

Detailed mapping of faults in the Smeaheia area has started focusing on both sealing potential of major faults in the area and leakage risk into the polygonal fault system in the overburden.

Tools for screening of critical stressed faults is under development together with a more detailed assessment of fault rock properties based on the spares data available.



Cross section of the Vette fault (V01) and the minor faults mapped in the footwall (FW02 and FW01). The work provides input for further structural analysis and models for fault reactivation.

CO_2 storage site containment (Task 10)

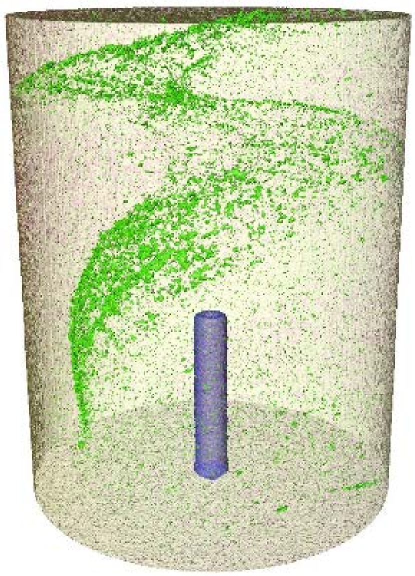
The focus is on leakage issues affecting sub-sea wells and the near-well area. The task is looking to maximise storage capacity with minimum risk of significant leakage. Through the research an atlas will be developed. The atlas will contain a check-list of well integrity issues compromising CO_2 storage success.

www.sintef.no/NCCST10

Results 2017

Task 10 deals with geomechanics and well integrity, focusing on derisking the well and near well area. The wells by which CO_2 is injected in a storage reservoir are identified as the largest risk for leakage from the reservoir. A laboratory activity was initiated to look at injectivity loss due to precipitation of salt near the wells. The first test resulted in massive clogging of the rock core, even though low salinity was chosen to match North Sea conditions.

A small activity also looked at developing geological fault description in geomechanical software, to help predict conditions for a leakage to occur along a fault. This activity relates to work being done in task 9 on faults. The in-house SINTEF software MDEM was used to look at injection conditions where a conductive path would be created in the weak zone alongside a fault.



Interpreted X-ray CT scan of a Berea core plug, an outcrop sandstone often used as field rock analogue. The plug had super-critical CO_2 flowing from the top, displacing the brine filling the rock's pores. The drying effect of the CO_2 flow caused salt to precipitate, here enhanced in green. This is thought to restrict pore throat diameter and hinder effective CO_2 injection.

Reservoir management and EOR (Task 11)

By pumping CO_2 into oil reservoirs and storing it there, we can extract more oil. This technique is called enhanced oil recovery (EOR). But, the cost of CCS is still too high, meaning the process capturing the CO_2 one intends to pump into the reservoirs is too expensive. Therefore, reducing net cost of the overall CCS chain is the main barrier addressed in this task. Good reservoir management is a huge part of that, as it will be imperative to minimize storage-related costs.

www.sintef.no/NCCST11

Results 2017

The mobility contrast between CO_2 and oil/water, and the large well distance, make tertiary CO_2 injection more challenging as an EOR option in the North Sea than in North America, where it is already being successfully employed.

The task investigates novel methods for controlling the mobility of injected CO_2, such as functionalized nanomaterials for foam generation or direct CO_2 thickeners.

Following a review of recent literature, the first series of newly designed POSS (polyhedral oligomeric silsequioxanes) nanomaterials was synthesized.

Testing of CO_2 solubility and other properties will commence in 2018, to give input on further generations of nanomaterials. Mobility control of injected CO_2 can also be beneficial for aquifer storage, since it could postpone the point in time when CO_2 reaches spill points in structural traps. Initial modelling to investigate this effect has been performed.

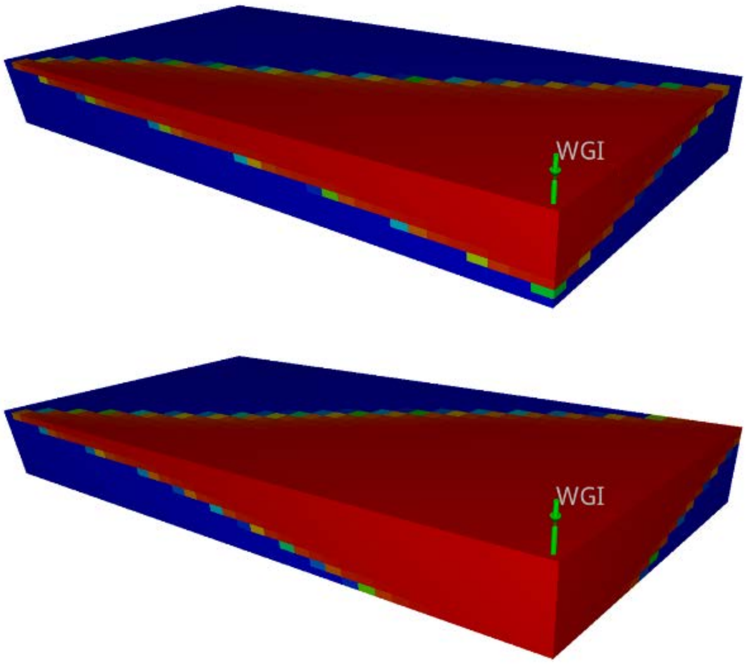


Illustration of the potential effect of CO_2 mobility control in aquifer storage. The simulation in the upper model is performed with normal CO_2 mobility, while in the lower model CO_2 mobility is reduced due to a CO_2-soluble foaming agent. The amount of CO_2 that can be injected before the front reaches the spill point at the left edge of the model is twice as large in the simulation with mobility control.

Cost-effective monitoring technology (Task 12)

One of the keys for safe CO_2 storage is that industry operators comply with monitoring regulations. Monitoring the storage site is potentially very expensive. The main ambition is to develop and demonstrate monitoring technology which will enable safe operation in compliance with laws and regulations in the most cost-efficient manner.

www.sintef.no/NCCST12

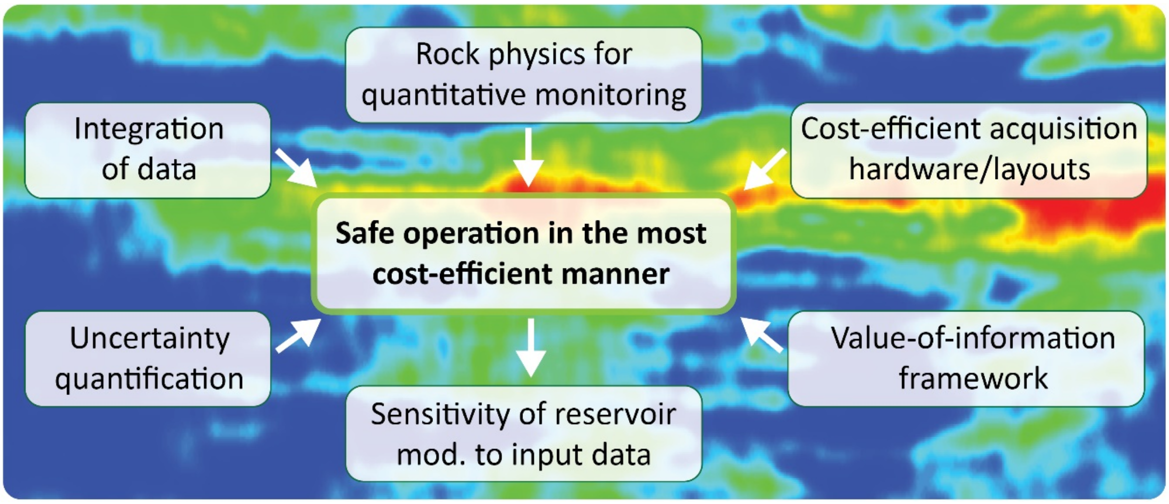
Results 2017

The task focused on setting up synthetic Smeaheia geophysical models, on developing new approaches for efficient use of available data for quantitative CO_2 monitoring, and on using a statistical value-of-information concept for cost-minimization of CO_2 monitoring.

For Smeaheia, Statoil's CO_2 injection simulations were used to build synthetic models of the subsurface acoustic velocity, resistivity, and density at different times during and after the injection. These models together with Smeaheia data provided by Gassnova will serve as very important input for targeted Smeaheia monitoring studies in the years to come in NCCS.

Work on quantitative CO_2 monitoring at Sleipner led to promising results that was presented at several workshops and conferences and published in several journals. In total, six publications were produced.

Industry partners Statoil, Shell and Total, as well as vendor Quad Geometrics have contributed to the task and participated in a workshop in September. Late in 2017, EMGS confirmed that they want to join the task as a vendor.



The main research objective is to develop and demonstrate monitoring technology enabling safe operation in compliance with laws and regulations in the most cost-efficient manner. In 2017, the focus was on preparing for future studies of monitoring at Smeaheia and on developing new approaches for quantitative monitoring and cost-efficient monitoring.

Innovation and technology transfer (ITT)

NCCS' main goal is fast-tracking CCS technology. This task will facilitate that by promoting an innovative environment through concrete cooperation between scientists and industry partners. The potential for spin-offs, start-ups or license agreements will be continuously investigated.

www.sintef.no/NCCSITT

Results 2017

In conjunction with the ITT Task, a case study of innovation management in six of the eight first FMEs were conducted. This work resulted in both a master thesis, and establishment of a methodology dubbed *The Innovation Management Wheel.* This is a shortlist of nine topics and ambitions the centre management should live by to be able to promote innovative output from the research collaboration in the centre. Now, this methodology is becoming a key part of the NCCS Innovation Framework.

Talk about innovation! Get innovation on the centre agenda and fill the word with content by defining activities and goals you all can understand and align to.

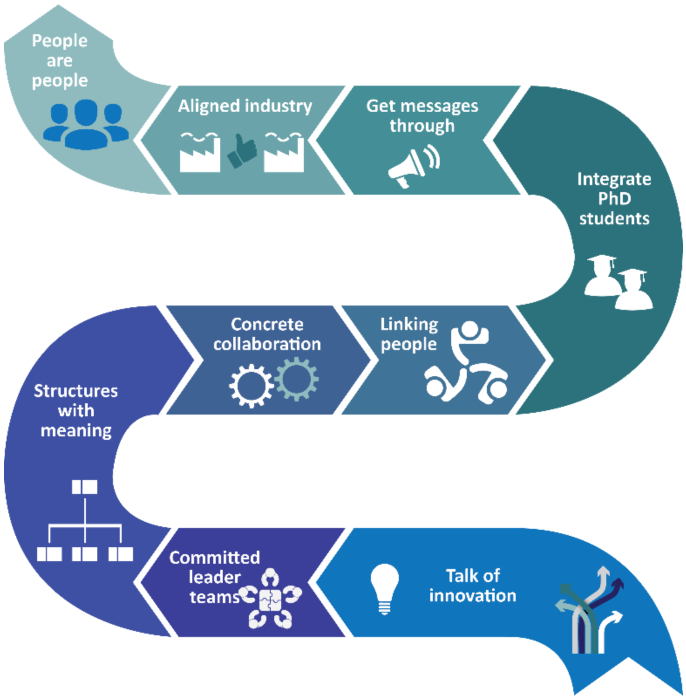
Build committed leader teams. A committed leader team will support holistic leadership of the centre by sending the same messages and attitudes through to all participants, at the same time as preventing opportunistic behaviour from partners.

Structures are nice, but… Organisational structures as innovation committees or reporting schemes will only promote innovative research given continuous attention and focus from management over time. Without management focus, such structures will potentially oppose innovation.

How concrete can it get? Real innovative output is created through real cooperation between researchers and the technical experts in the industry, with concrete contributions and dependencies from both sides.

Link the right people! Create arenas where people can meet and get to know, understand and trust each other.

Get the full value of your PhDs! Integrate the PhD students closely into your centre such that the students feel they are part of something bigger than themselves and such that the industry feel the relevance of their work.



The figure illustrates The Innovation Management Wheel, a methodology developed in conjunction with NCCS for promoting innovative output from the centre.

Never (ever) forget to rally your troops! Never underestimate the effort it takes to communicate messages or implement a change throughout your centre organisation.

Get industry partners to talk to each other! Industry partners who talk to each other and align their expectations towards the research centre will contribute to holistic leadership and to reducing conflicts in the centre.

People, people, people! Managing innovation is really all about managing people.

International Cooperation

Activities on the strategic arena

Active participation in organizations spearheading the strategic CCS development on the European arena, is a priority for NCCS. In this way, Norway and NCCS is able to contribute in the stage-setting of the research agenda in the field of CCS.

As of May 3, 2017, Dr. Nils Røkke is the Chairman of the European Energy Research Alliance (EERA).

With 175 research centre and university members from 27 countries, EERA's objective is to build on national and European research initiatives and to be the cornerstone in the European Strategic Energy Technology Plan (SET Plan).

Dr. Nils A Røkke has since 2010 been co-chair of the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP). ZEP is a coalition of stakeholders united in their support for CO2 capture and storage as a key technology for combating climate change. ZEP serves as advisor to the European Commission on the research, demonstration and deployment of CCS.

The CCS Joint Programme under the EERA (EERA JP-CCS) is an authority on CCS research, development and innovation. The CCS-JP provides strategic leadership to its energy research partners. Furthermore, it coordinates both national and European R&I programs to maximize synergies, facilitates knowledge sharing and delivers economies of scale to accelerate the development of CCS.

Dr. Marie Bysveen has held the coordinator role in JP-CCS since 2015.

Horizon 2020 activities

Participants in NCCS are active in ongoing H2020 projects, including CO_2 capture from cement (CEMCAP) with a project period from 2015-2018. In addition, NCCS partners are leading and/or active in five ACT-ERA-Net Co-fund projects that started in 2017. It is also envisioned that NCCS partners will be building consortia for new calls in the H2020 framework, especially in the area of "Enabling near-zero CO_2 emissions from fossil fuel power plants and carbon intensive industries". The most relevant calls are:

- LC-SC3-NZE-1-2018: Advanced CO_2 capture technologies
- LC-SC3-NZE-3-2018: Strategic planning for CCUS development
- LC-SC3-NZE-4-2019: Integrated solutions for flexible operation of fossil fuel power plants through power-to-X-to-power and/or energy storage
- LC-SC3-NZE-5-2019-2020: Low carbon industrial production using CCUS

Other initiatives

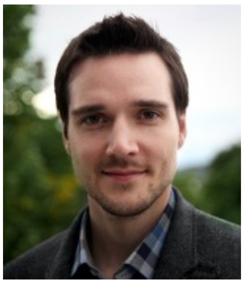
NCCS has agreed to host the IEAGHG Summer School 2018. The Summer Schools are the only CCS education program to have a truly international focus, and has now taken place in seven countries covering Europe, Australia, Asia and North America. The Summer School aspires to include a diverse range of students from a variety of technical backgrounds. Over 550 alumni representing more than 50 countries, have attended so far. Up to 60 students attend and the event each time, and the school runs over a packed five-day schedule. The week includes a fieldtrip and a day is set aside for networking, career talks, and group work presentations.

The NCCS Special Advisory Group (SAG) is established with world leading experts in the CCS field. SAG shall advise the NCCS Board on strategic issues such as trends and new developments, and help position the Centre globally. The Committee consists of: Kelly Tambimuhtu (IEAGHG), Karen Wesley (Shell), Niall Mac Dowell (Imperial College London), Katherine Romanak (Univ. Texas), Julio Friedman (Energy Futures Initiative), Mike Monea (SaskPower), Brad Page (Global CCS Inst.), Jon K. Økland (Gassco), Hans J. Vinje (Gassnova), Marie Bysveen (EERA), and Nils Røkke (SINTEF). The group is chaired by Nils A. Røkke.

Preparations have been initiated to establish the NCCS Scientific Committee (SC). The SC is an advisory committee with leading international capacities giving guidance to the Centre on scientific progress and quality. Prof. Philip Ringrose, NTNU/Statoil, will chair the committee, and the aim is to have the SC in operation during the first half of 2018.

Facilitating mobility of researchers and students is a priority. As important as sending NCCS personnel to external organizations, is to attract NCCS externals to the Centre. Concrete plans so far include that:

- Ruhr University sends: one PhD student to NTNU (2 years), one PhD student to NIST (3 months) one MSc student to SINTEF (3 months)
- SINTEF sends one of the NCCS Task leaders, Jonathan Polfus, to MIT (6 months)



An application (Fast TraCCS, NOK 4.5 mill.) for additional funding of mobility activities was submitted to the International Partnerships for Excellent Education and Research (INTPART) on May 24, 2017, but unfortunately not granted. New possibilities will be explored for extra mobility funding.

The NCCS Director and Centre Manger have interacted with the US National Energy Technology Laboratory (NETL), and the UK CCS Research Centre (UKCCSRC). Plans for cooperation with these two organizations are being developed. Among other things the Centre Director has accepted a seat in the UKCCSRC Board. Furthermore, the Centre Manager has accepted to be a Steering Committee member at the Society of Petroleum Engineers (US) and to co-organize a CCS Experts Forum in Italy in 2018, together with Imperial College and the Department of Energy's National Energy Technology Laboratory (NETL).

Recruitment

One of the most important tasks of NCCS is to educate master's and doctoral students in CCS research so that they can continue this knowledge in the work of CCS, whether they work in industry or as researchers. During the first year, 4 PhD fellows have been recruited and 3 postdoctoral fellows are in the starting pit.

PhD Candidates

Name: **Venja Buvik**
Period: 2017-2021
Task: 2
Title: **Effects of amine structure on solvent stability of CO_2 absorbents**

Name: **Stefan Herrig**
Period: 2013-2018
Task: 8
Title: **New Helmholtz-Energy Models for Pure Fluids and CCS-Relevant Mixture**

Name: **Jonathon Osmond**
Period: 2017-2021
Task: 9
Title: **3D structural characterization and containment risk analysis of two CO_2 storage prospects in the Smeaheia area of the Northern Horda Platform, Norwegian North Sea**

Name: **Mats Rongved**
Period: 2015-2018
Task: 10
Title: **Hydraulic Fracturing for Enhanced Geothermal Systems**

Postdoc Candidates

Name: **Mark Mulroony**
Period: 2017-2021
Task: 9
Title: **Structural de-risking of the Smeaheia CO_2 storage prospect**

Name: **Ozgu Turgut**
Period: 2017-2019
Task: 1
Title: **Value Chain Optimization of Carbon Capture and Storage for Stationary Emitters**

Name: **Tafara Makuni**
Period: 2017
Task: 5
Title: **Experimental investigations into forced and self-excited azimuthal combustion dynamics modes**

Communication and Dissemination

CCS deployment requires industrial and political willingness as well as public acceptance. Open and engaging communication of scientific results is therefore a strategic activity in *NCCS.* Communication in NCCS aims to extend communication beyond the *NCCS* consortium and scientific community to provide facts in the public CCS debate, promote innovations to industry and *help* increase public support for CCS.

Communication in numbers

- Information material/blogs 30
- Media contributions 5
- Newsletters 4

Communication channels

Web

The NCCS web – www.nccs.no – was launched in 2016. The webpage provides open information from the centre.

- The web has had 651 unique visitors.
- There have been 2894 views on the webpages.
- Visitors to the webpage come mainly from Norway, United Kingdom, United States, Canada, India and Germany.

Newsletter

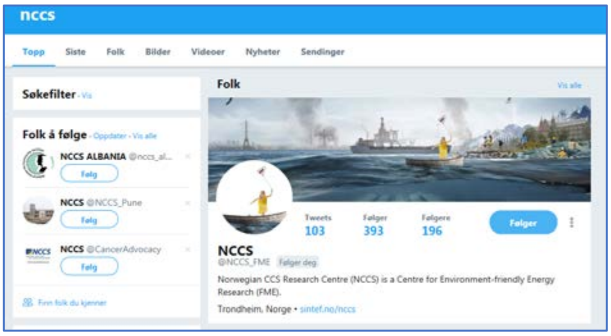
4 newsletters were sent to more than 2500 subscribers.

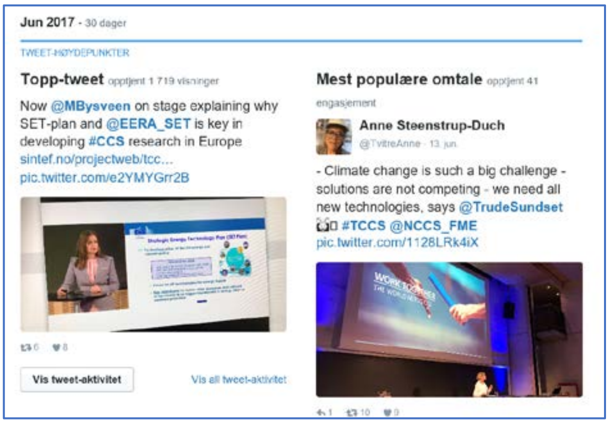
- December 22, 2017: NCCS newsletter #4
- October 20, 2017: NCCS newsletter #3
- October 11, 2017: NCCS newsletter #2
- September 14, 2017: NCCS newsletter #1: TCCS-9 highlights, opening of new ECCSEL lab, lifting of 8 ton rig (video) and more...

Twitter NCCS

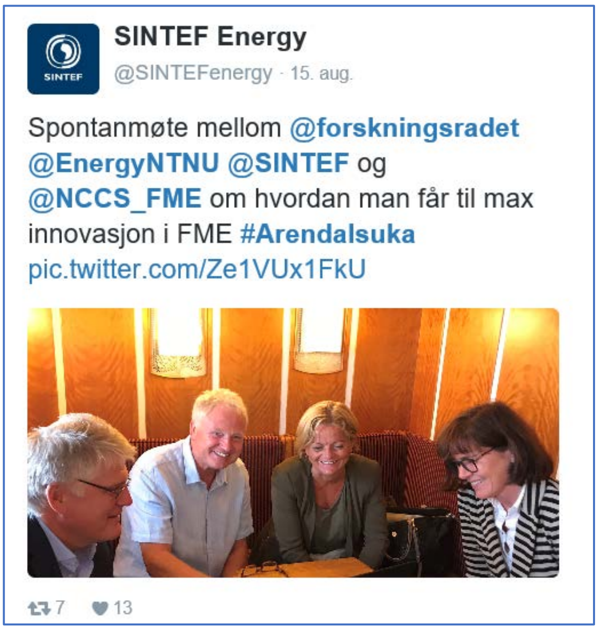
NCCS has a twitter account were conferences and news about CCS is shared.

NCCS has 393 followers with more than 35 000 views since the account was opened May 2017. In June, during TCCS-9, the account had more than 18 000 views alone.





A top-tweet in August was when Centre Director Mona Mølnvik met key innovation actors during Arendalsuka.



Media contributions
In order to reach a wider audience, NCCS has published op-eds and contribute to media coverage of CCS. Here are some examples:

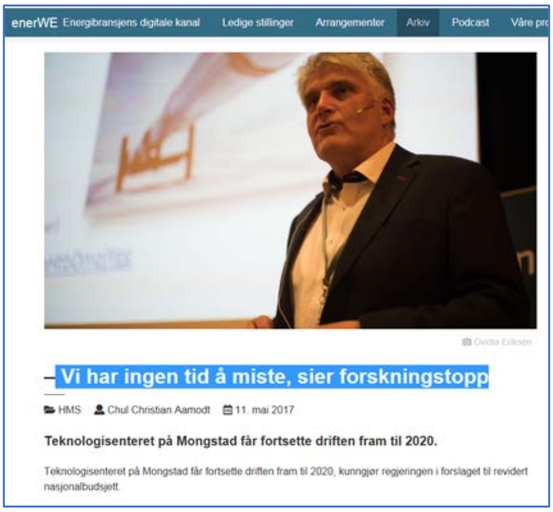
TU 2017-01-30
[I Energilaboratoriet pp Tiller fanger de CO2 med en ny metode]


«CHEMICAL LOOPING COMBUSTION» (CLC)
I energilaboratoriet på Tiller fanger de CO2 med en ny metode
Krever mindre energi.

Verden kommer ikke unna fangst og lagring av CO2 om vi skal klare klimaforpliktelsene våre. Dette krever store investeringer for både fangst, transport og lagring av CO2.

Men teknologiene er fortsatt ikke tatt i bruk i kommersiell sammenheng.

EnerWE 2017-05-11
[Vi har ingen tid å miste, sier forskningstopp]


enerWE Energibransjens digitale kanal Ledige stillinger Arrangementer Arkiv Podcast

– Vi har ingen tid å miste, sier forskningstopp
HMS Chul Christian Aamodt 11. mai 2017

Teknologisenteret på Mongstad får fortsette driften fram til 2020.

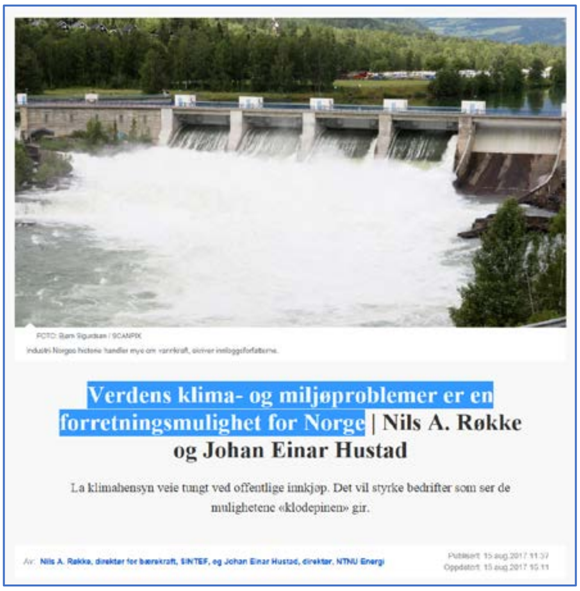
Teknologisenteret på Mongstad får fortsette driften fram til 2020, kunngjør regjeringen i forslaget til revidert nasjonalbudsjett.

TU 2017-06-11
Klimakrisen kan tvinge oss til å suge CO2 fra lufta. Dette er det første kommersielle anlegget som gjør det


CLIMEWORKS
Klimakrisen kan tvinge oss til å suge CO2 fra lufta. Dette er det første kommersielle anlegget som gjør det
Samler CO2 tilsvarende utslippet fra rundt 200 biler.

Aftenposten 2017-08-15

[Verdens klima- og miljøproblemer er en forretningsmulighet for Norge]

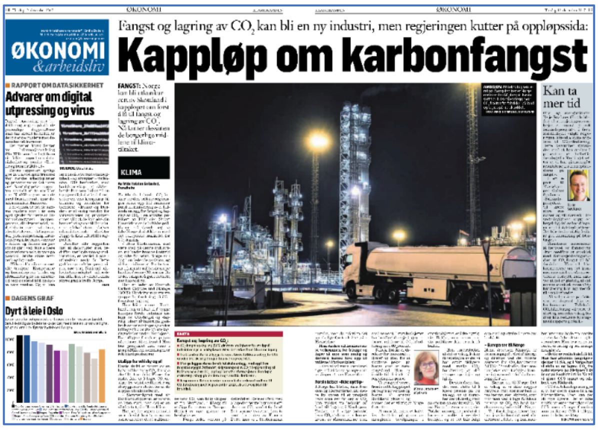


Verdens klima- og miljøproblemer er en forretningsmulighet for Norge | Nils A. Røkke og Johan Einar Hustad

La klimahensyn veie tungt ved offentlige innkjøp. Det vil styrke bedrifter som ser de mulighetene «klodepinen» gir.

Klassekampen 2017-12-12

[Kappløp om karbonfangst]



ØKONOMI & arbeidsliv

Fangst og lagring av CO_2 kan bli en ny industri, men regjeringen kutter på oppløpssida:

Kappløp om karbonfangst

Advarer om digital utpressing og virus

Dyrt å leie i Oslo

Kan ta mer tid

Energi og klima 2017-12-12
[Ekspertintervjuet: Karbonfangst kan bli nøkkelen](#)


ENERGI KLIMA
2°C
Ekspertintervjuet: Karbonfangst kan bli nøkkelen
Lars Ursin
Selv om all industri i verden brukte fornybare energikilder, er det fortsatt prosesser som avgir klimagasser. Hvis vi kan fange disse gassene effektivt, er mye gjort, sier forskningsdirektør Mona Mølnvik ved SINTEF.
12. desember 2017
Ekspertintervjuet:

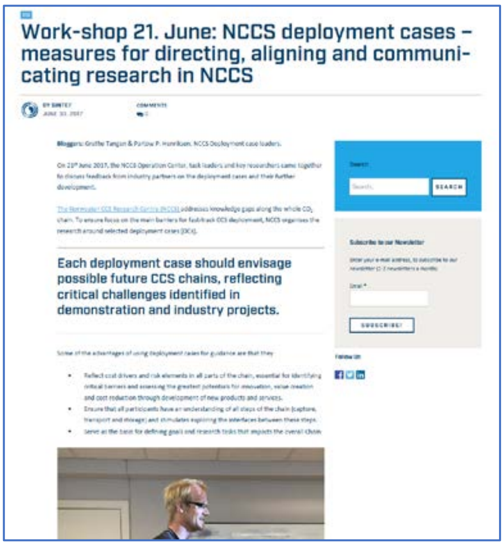
Klassekampen 2017-12-16
[Mot null utslipp](#)


KLASSEKAMPEN NYHETER
Fangst og lagring av CO_2 er kostbart, men mulig:
Mot null utslipp
REALISME: Mange forbinder CO_2-rensing med fadesen på Mongstad. – Nå er situasjonen en helt annen, sier forsker.
MILJØ
«Det er mye mer realistisk å lykkes med CCS nå enn for ti år siden. Spørsmålet er om vi har råd til å la være»
Norsk Industri: – Nå haster det

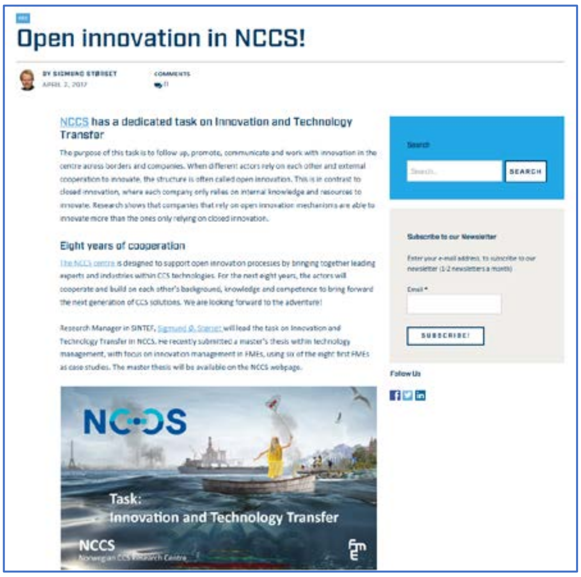
Blogs
NCCS has contributed to several blogs in 2017. All the blogs are published on the #SINTEFblog
https://blog.sintef.com/tag/nccs-en/

- [Hydrogen is on a mission to decarbonise the world](#) - 1 180 readers
- [TCCS-9: Two days of CCS research and innovation in 750 words](#) - 298 readers
- [Work-shop: How should we communicate CCS?](#) - 151 readers

#SINTEFblog 2017-06-30
[Work-shop 21. June: NCCS deployment cases – measures for directing, aligning and communicating research in NCCS]

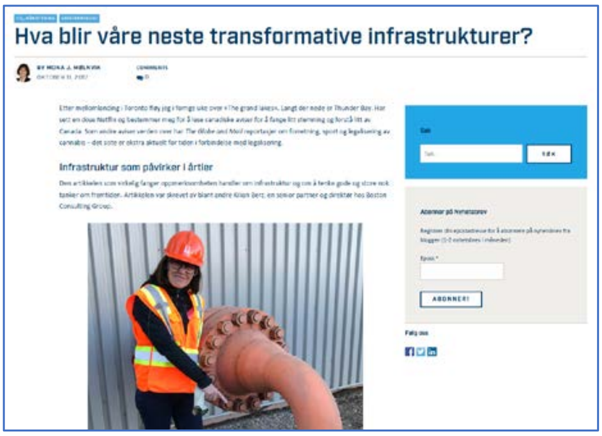


#SINTEFblog 2017-04-02
[Open innovation in NCCS!]

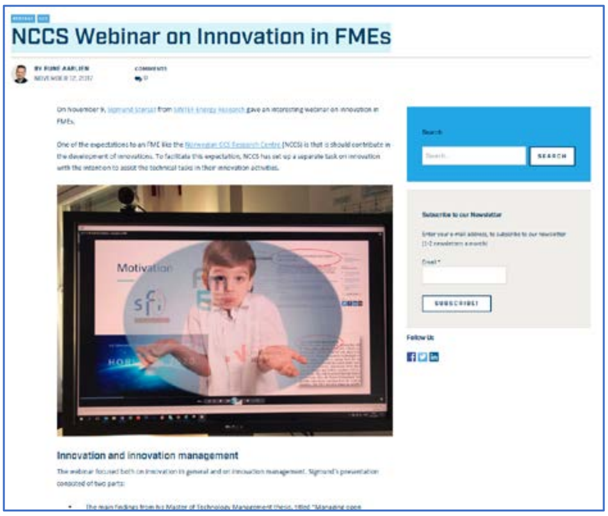


#SINTEFblog 2017-08-15
[Arendalsuka: Forskning virker og er viktig for rask implementering av CCS i full skala]

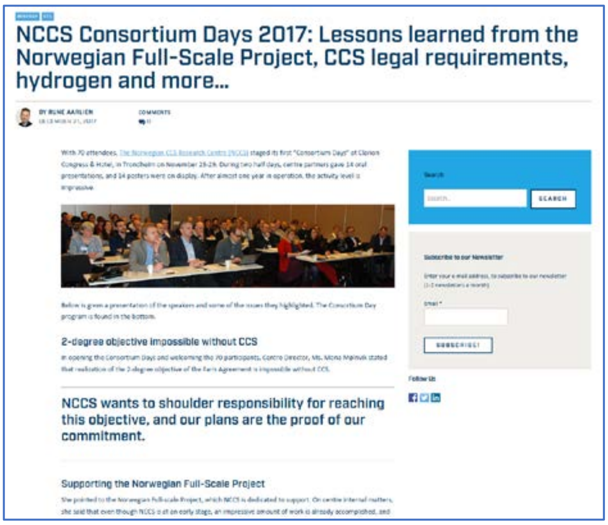
#SINTEFblog 2017-10-11
[Hva blir våre neste transformative infrastrukturer?]



#SINTEFblog 2017-11-12
[NCCS Webinar on Innovation in FMEs]



#SINTEFblog 2017-12-21
[NCCS Consortium Days 2017: Lessons learned from the Norwegian Full-Scale Project, CCS legal requirements, hydrogen and more…]



APPENDIXES

A1. Personnel

NCCS Key Researchers

Name	Institution	Main research area	Task
Simon Roussanaly	SINTEF Energy Research	CO_2 value chain and techno-economic modelling	1
Geir kaugen	SINTEF Energy Research	Thermodynamic and process optimisation	1
Han Deng	SINTEF Energy Research	Thermodynamic and process optimisation	1
Asgeir Tomasgard	NTNU	Industrial economics	1
Ozgu Turgut	NTNU	Industrial economics	1
Vegard Bjerketvedt	NTNU	Industrial economics	1
Catherine Banet	UiO	Legal	1
Solrun Johanne Vevelstad	SINTEF Industry	Post combustion CO_2 capture	2
Andreas Grimstvedt	SINTEF Industry	Post combustion CO_2 capture	2
Merete Wiig	SINTEF Industry	Post combustion CO_2 capture	2
Inna Kim	SINTEF Industry	Post combustion CO_2 capture	2
Hanna Knuutila	NTNU	Post combustion CO_2 capture	2
Peter van Os	TNO	Post combustion CO_2 capture	2
Earl Goeether	TNO	Post combustion CO_2 capture	2
Juliana Garcia Moretz-Sohn Monteiro	TNO	Post combustion CO_2 capture	2
Jonathan Polfus	SINTEF Industry	Ceramic membranes	3
Zuoan Li	SINTEF Industry	Ceramic membranes	3
Harald Malerød-Fjeld	CoorsTek Membrane Sciences	Ceramic Membranes	3
David Berstad	SINTEF Energy Research	CO_2 liquefaction	4
Stian Trædal	SINTEF Energy Research	CO_2 liquefaction	4
Jacob Stang	SINTEF Energy Research	CO_2 liquefaction	4
Andrea Gruber	SINTEF	Numerical modelling of reactive flows	5
Gonzalo del Alamo	SINTEF	Chemical kinetics modelling	5
James R Dawson	NTNU	Experimental combustion dynamics	5
Nicholas Worth	NTNU	Experimental combustion dynamics	5
Rahul Anantharaman	SINTEF Energy Research	CO_2 capture process integration and design	6
Chao Fu	SINTEF Energy Research	Process modelling and integration	6
Vidar Skjervold	SINTEF Energy Research	Process modelling	6
Kristin Jordal	SINTEF Energy Research	CO_2 capture process integration and design	6
Svend Tollak Munkejord	SINTEF Energy Research	CO_2 transport	7
Stéphane Dumoulin	SINTEF Industry	CO_2 transport	7
Gaute Gruben	SINTEF Industry	CO_2 transport	7
Morten Hammer	SINTEF Energy Research	CO_2 transport	7
Han Deng	SINTEF Energy Research	CO_2 transport	7
Sigurd Weidemann Løvseth	SINTEF Energy Research	CO_2 Thermodynamics / Fiscal metering	8
Snorre Foss Westman	SINTEF Energy Research	CO_2 Thermodynamics	8
Anders Austegard	SINTEF Energy Research	CO_2 Thermodynamics / Fiscal metering	8
Jacob Stang	SINTEF Energy Research	CO_2 Thermodynamics / Fiscal metering	8
Han Deng	SINTEF Energy Research	CO_2 Fiscal metering	8
Roland Span	Ruhr Universität-Bochum	CO_2 Thermodynamics	8
Stefan Herrig	Ruhr Universität-Bochum	CO_2 Thermodynamics	8
Tobias Neumann	Ruhr Universität-Bochum	CO_2 Thermodynamics	8
Edward Jukes	Krohne Ltd	CO_2 Fiscal metering	8

Alvar braathen	UiO	Structural geology	9
Elin Skurtveit	NGI/UiO	Structural geology	9
Jung Chan Choi	NGI	Geomechanics	9
Jan Inge Faleide	UiO	Geophysics	9
Ingrid Anell	UiO	Geology	9
Kim Senger	UNIS	Structural geology	9
Pierre Cerasi	SINTEF Industry	Geomechanics, leakage de-risking	9, 10
Malin Torsæter	SINTEF Industry	Well integrity, leakage de-risking	10
Jelena Todorovic	SINTEF Industry	Well integrity, injectivity impairment	10
Torbjørn Vrålstad	SINTEF Industry	Well integrity, injectivity impairment	10
Alv-Arne Grimstad	SINTEF Industry	CO_2 storage	11
Per Bergmo	SINTEF Industry	CO_2 storage	11
Torleif Holt	SINTEF Industry	CO_2 storage	11
Monika Pilz	SINTEF Industry	CO_2 storage	11
Juan Yang	SINTEF Industry	CO_2 storage	11
Eirin Langseth	SINTEF Industry	CO_2 storage	11
Christian Simon	SINTEF Industry	CO_2 storage	11
Christian Bos	TNO	CO_2 storage	11
Frank Wilschut	TNO	CO_2 storage	11
Peder Eliasson	SINTEF Industry	CO_2 storage	12
Bastien Dupuy	SINTEF Industry	CO_2 storage	12
Anouar Romdhane	SINTEF Industry	CO_2 storage	12
Amir Ghaderi	SINTEF Industry	CO_2 storage	12
Etor Querendez	SINTEF Industry	CO_2 storage	12
Halvor Møll Nilsen	SINTEF Digital	CO_2 storage	12
Odd Andersen	SINTEF Digital	CO_2 storage	12
Joonsang Park	NGI	CO_2 storage	12
Guillaume Sauvin	NGI	CO_2 storage	12
Jim White	BGS	CO_2 storage	12
Hayley Vosper	BGS	CO_2 storage	12
Gareth Williams	BGS	CO_2 storage	12
Ola Eiken	Quad Geometrics	CO_2 storage	12
Sigmund Ø. Størset	SINTEF Energy Research	CO_2 capture and process integration, innovation management	ITT
Grethe Tangen	SINTEF Industry	CO_2 storage	ITT
Jon Magne Johansen	SINTEF Energy Research	Innovation management	ITT

Postdoctoral researchers with financial support from the Centre budget

Name	Nationality	Period	Sex M/F	Topic	Task
Tafara Makuni	UK	07/2017 - 12/2017	F	Experimental investigations into forced and self-excited azimuthal combustion dynamics modes	5
Mark Mulrooney	Irland	09/2017 - 08/2021	M	Structural de-risking of the Smeaheia CO_2 storage prospect	9
Ozgu Turgut	Turkey	12/2017 - 11/2019	F	Value chain optimization of carbon capture and storage for stationary emitters	1

PhD students with financial support from the Centre budget

Name	Nationality	Period	Sex M/F	Topic	Task
Vanja Buvik	Norway	09/2017 - 08/2021	F	Effect of amine structure on solvent stability of CO_2 absorbents	2
Stefan Herrig	Germany	10/2013 - 07/2018	M	New Helmholtz-energy models for pure fluids and CCS-relevant mixtures	8
Jonathon Osmond	USA	10/2017 - 09/2021	M	3D structural characterization and containment risk analysis of two CO_2 storage prospects in the Smeaheia area of the Northern Horda Platform, Norwegian North Sea	9

PhD students working on projects in the centre with financial support from other sources

Name	Funding	Nationality	Period	Sex M/F	Topic	Task
Mats Rongved	KPN project	Norway	08/2015 - 03/2018	M	Hydraulic fracturing for enhanced geothermal systems	10

Master degrees

Name	Sex M/F	Topic	Task
Isabella Stellwag	F	Testing of oxygen removal technology	2
Avinash S.R. Subramanian	M	Reducing energy consumption in the production of hydrogen from natural gas	6
Niklas Hunka	M	Description of accurate viscosity setup for CCS	8
Hong Yan	F	Rock physics inversion for CO_2 characterization at Sleipner	12
Veronica Alejandra Torres Caceres	F	Seismic wave attenuation in partially saturated sandstone and AVO analysis for carbon dioxide quantification at Sleipner	12

A2. Statement of Accounts

(All figures in 1000 NOK)
As an option the funding and cost for each partner may be presented
and also, how funding and cost is allocated to the subprojects in the centre.

Funding

Funding	**Amount (kNOK)**
The Research Council	24 276
SINTEF Energy Research (host)	6 457
Research Partners	9 215
Enterprise partners	5 343
Public partners	1 101
TOTAL	**46 392**

Costs	
SINTEF Energy Research (host)	20 245
Research partners	20 855
Enterprise partners	1 489
Public partners	3 804
Equipment	0
TOTAL	**46 392**

A3. Publications

Journal papers

Dupuy, Bastien; Romdhane, Anouar; Eliasson, Peder; Querendez, Etor; Yan, Hong; Torres Caceres, Veronica Alejandra; Ghaderi, Amir.
Quantitative seismic characterisation of CO_2 at the Sleipner storage site, North Sea. Interpretation 2017; Volume 5.(4) pp. SS23-SS42

Møyner, Olav and Nilsen, Halvor Møll.
Multiresolution coupled vertical equilibrium model for fast flexible simulation of CO_2 storage. arXiv.org, 2017

Published conference papers

Dupuy, Bastien; Romdhane, Anouar; Eliasson, Peder; Yan, Hong; Torres Caceres, Veronica Alejandra; Querendez, Etor; Ghaderi, Amir.
Carbon dioxide saturation estimates at Sleipner using seismic imaging and rock physics inversion. EAGE/SEG Research Workshop 2017 on Geophysical Monitoring of CO_2 Injection: CCS and CO_2-EOR. European Association of Geoscientists and Engineers 2017 ISBN 9781510850781, pp. 122-126

Reports

Yan, Hong.
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CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

The Research Council of Norway

NCCS – Industry driven innovation for fast track CCS deployment

NCCS is a Centre for Environment-friendly Energy Research (FME). The objective of the FME-scheme is to establish time-limited research centres which conduct concentrated, focused and long-term research of high international calibre.

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