2009–2017

BIGCCS

International CCS Research Centre

FINAL REPORT

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

DEAR CCS FRIENDS,

We have arrived at the end of BIGCCS

Looking back, it was a magnificent journey, coloured with great scientific achievements, hard work, and the development of friendships and strong relations between researchers, industry experts, PhD students and professors and last, but not least, the Research Council of Norway.

In the BIGCCS proposal we said: *"The BIGCCS Centre aims at providing crucial knowledge and a basis for technology breakthroughs required to accelerate the development and deployment of large-scale CCS enhanced by comprehensive international co-operation. The fulfilment of this objective relies on long-term, targeted basic research of high scientific quality, professional management, and international user partner involvement."*

I'm happy to say we achieved our objective.

I'm happy to say we achieved our objective. The CCS road is a long and winding one, but BIGCCS played its part. I know that the knowledge base, results, and innovation projects spun off from the Centre plays an important role in the advancement of full-scale CCS. We were early movers in the area of industrial CCS, and it is both interesting and promising that the full-scale CCS project in Norway is based on capturing CO_2 from industry sources.

Another of our objectives read: *"To recruit and educate personnel, of which 50% are women, with first-class competence within CCS related topics (18 PhDs, 8 post-docs, 50 MSc graduates) to ensure recruitment both to industry and research institutions."*

The BIGCCS Centre and the add-on premium projects together educated 26 PhDs and 8 Postdocs, a big overachievement.

You can read the rest of the BIGCCS story in this exciting report. You will find a comprehensive summary of the eight years of joint efforts in addressing one of our time's largest challenges: climate change.

In December 2015, the Paris Climate Agreement was adopted by consensus and it came into force on November 4, 2017. As the *only* technology that can substantially reduce CO_2 emissions from fossil fuels, CCS is essential to limit global warming. Indeed, without CCS, it will be extremely difficult to keep the rise in global temperature within the limits set by the Paris Agreement. CCS is also the *only* means of achieving deep emissions cuts in industries such as steel, cement and petrochemical. So, our work is far from over, and we look forward to continuing with the FME NCCS.

Mona J. Mølnvik, Director BIGCCS

- BIGCCS provided stability and excellent scientific progress in turbulent times for CCS, during the initial stages of what has been termed the energy and climate revolution. With the Paris Agreement now in place, the results and achievements of BIGCCS will be invaluable for reaching global, European and national climate and energy goals.

Nils A. Røkke, Chairman BIGCCS Board

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FOREWORD – HOST INSTITUTION

SINTEFs vision is "Technology for a better society". Few research centres can claim the vision with such strength as BIGCCS. In it's eight year history it has produced excellent, relevant science and innovation for the CCS industry.

BIGCCS stands on the shoulders of a proud CCS history that began at NTNU and SINTEF in the 1980s. BIGCCS had taken one big leap closer to implementing CCS full-scale.

BIGCCS has brought the industry closer to the science community and strengthened the CCS co-operation between the science institutions involved.

SINTEF Energy's mission is to shape tomorrow's energy solutions. Our focus areas, including CCS, shall contribute towards the transition to future, sustainable, energy systems. Reading the results in this report, I am convinced BIGCCS has fulfilled this mission. BIGCCS has contributed to an increase in scientific publications, innovations, attracting new talents, and given CCS visibility internationally, especially in Europe.

The size and longevity of the Centres for Environment-friendly Energy Research (FME) gives an impact on the international arena, in particular in Europe. The centre has had a high international profile with close collaboration with strong European industry partners and highly ranked international research institutions. Consequently, the Centre has extended the research network of the partners involved. The Centre has also been a successful platform for European spin-off H2020-projects such as CEMCAP, Gateway and ECCSEL, and other large projects.

BIGCCS has brought the industry closer to the science community and strengthened the CCS co-operation between the science institutions involved.

Knowledge commits. Norway has world-class science on CCS. Thus, we have a special responsibility in leading the way. The Norwegian Government has taken this responsibility in the Norwegian full-scale project. Our new FME centre, NCCS will support this effort, and I look forward to following its efforts and achievements in the future.

Inge R. Gran,
President SINTEF Energy Research

SUMMARY

At the outset of the BIGCCS Centre, our philosophy was “Yes, we can!”.
Eight years of concentrated efforts and dedication proved that statement correct.

Contributions to FME overall goals

The Centre worked steadily towards the targets and the overarching objectives of the Norwegian Parliament’s Climate Agreement from 2008. New tools and models were created to assess CO_2 storage capacity and qualification in close co-operation with the industry. This will enable more widespread carbon dioxide storage on the Norwegian Continental Shelf. A basis has been created for innovations and important spin-off projects that will contribute to lower cost and new value chains for petroleum in a low emission society, and reduced GHG emissions in Norway and around the world. The Centre pioneered new knowledge and processes for transport of CO_2 by ships and pipelines by optimizing the process at the interfaces of capture, transport and storage. Finally, BIGCCS initiated and promoted international co-operation to secure uptake of the results at a global scale.

Yes, we can!

Results

Examples of exciting and promising results from the Centre are many:

- New solvent systems and processes
- Membrane separation of hydrogen
- New burner concepts to enable combustion of hydrogen-rich fuels in gas turbines with controlled nitrous oxide emissions and high efficiency
- New chemical looping technology
- A new model for design of safe CO_2 transport pipelines
- Highly accurate experimental thermophysical properties of CO_2-rich mixtures
- An automated CO_2 leakage detection tool
- Improved quantification of uncertainty in geophysical monitoring methods
- Technology for use of CO_2 for closing cracks in well cement
- Method for manipulating cement-steel bonding in CO_2 wells
- Improved monitoring technologies for CO_2 storage with significantly reduced uncertainty
- Understanding of fundamental effects of CO_2 injection on storage reservoirs and caprock
- Understanding of the effects of large-scale storage on the reservoirs
- The iCCS tool for multi-criteria assessment of CO_2 value chains

BIGCCS researchers registered 675 contributions to the CRIStin publications database – 219 of these were peer reviewed articles. Individuals connected to the Centre received the *IEA Greenman Award* twice, and the *SINTEF and NTNU CCS Awards* three times.

With industry in focus

The continuous focus on generating useful results for industry resulted in 46 documented innovations at various stages on the TRL scale. Researchers will develop some of them further, while others are already at the disposal of the industry partners. Ultimately, it is up to industry to take them to market.

The new generation

The education program included 26 PhDs, 8 Postdocs, and 52 MSc students with CCS-related topics. Only one PhD failed to complete and only 10 additional months were required by all other candidates. 21 professors were active in supervision of the candidates. Four of the candidates – Christian Eichler, Georg Baumgartner, Sissel Grude, and Chao Fu – were given special recognition for their work.

Shouldering international responsibility

BIGCCS took an active role in the development of European CCS strategies both at the research and academic levels. In particular, the involvement focused on *The CCS Joint Programme under the European Energy Research Alliance* (EERA JP-CCS) and *The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)*, where we held leading positions and contributed to strategy development.

SINTEF is the coordinator of three EU projects with topics relevant to the Centre activities. GATEWAY and CEMCAP (both Horizon 2020), and IMPACTS (FP7) are all projects that strengthened the competence base of BIGCCS.

The Centre was fortunate to cooperate closely with Sandia National Laboratory and University of Berkeley, two of the leading institutions in combustion technology, which resulted in a fruitful exchange of researchers.

There was an active cooperation between BIGCCS and the Norwegian node of the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL), which is designed to give researchers access to quality research infrastructure devoted to CCS technologies.

The Trondheim Conference on CCS (TCCS) is an important meeting arena for CCS researchers, bringing together roughly 400 participants from all around the world every two years. BIGCCS organized TCCS three times, in 2011, 2013, and 2015.

The added value of an FME Centre

The long duration of an FME offers several advantages. It provides an excellent foundation from which new projects can be spun off and complement ongoing Centre activities. The creation of strong and lasting networks – both nationally and internationally – is another upside. With projects lasting so long, individuals and organizations are willing to invest more time and resources to develop lasting relations that in the end can foster new opportunities and generate closer project cooperation. Status as a Centre also means increased visibility. Our Centre partners have become increasingly popular as partners in new project applications, which is a valuable asset for the future.

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SAMMENDRAG

Da vi startet BIGCCS, var vår filosofi «ja, vi kan!».
Åtte år med konsentrert innsats og høyt engasjement viste at filosofien var berettiget.

Bidrag til FME ordnede mål

Det er arbeidet jevnt og trutt mot de overordnede målene i Stortingets klimaforlik fra 2008. Nye verktøy og modeller er utviklet for å urdere lagringspapasistet for CO_2 og kvalifisering av brønner i nært samarbeid med industrien. Dette vil muliggjøre lagring av større volumer av karbondioksid på norsk sokkel. Et fundament er opprettet for innovasjoner og viktige spin-off prosjekter, som vil bidra til lavere kostnader og nye verdikjeder for petroleum i lavutslippssamfunnet, og reduserte klimagassutslipp i Norge og rundt om i verden. Senteret har utviklet banebrytende ny kunnskap og nye måter for transport av CO_2 med skip og i rør ved prosessoptimalisering i grensene mellom fangst, transport og lagring. I tillegg har BIGCCS initiert og fremmet internasjonalt samarbeid for å sikre at resultatene nyttiggjøres i global skala.

Ja, vi kan!

Resultater

Eksempler på spennende og lovende resultater fra senteret er mange:

- Nye systemer og prosesser med solventer
- Hydrogenseparasjon ved hjelp av membraner
- Nye brennerkonsepter for å muliggjøre forbrenning av hydrogenrike brennstoffer i gassturbiner med kontrollerte utslipp av nitrogenoksider og høy effektivitet
- Ny kjemisk looping-teknologi
- En ny modell for sikker utforming av CO_2-transport-rørledninger
- Svært nøyaktige målinger av termofysiske egenskaper av CO_2-rike blandinger
- Et automatisert lekkasjedeteksjonsverktøy for CO_2
- Forbedret kvantifisering av usikkerheten i geofysiske metoder for lagringsovervåking
- Teknologi for anvendelse av CO_2 for tetting av sprekker i brønnsement
- Metode for manipulering av sement-stål bindinger i CO_2-brønner
- Bedre overvåkingsteknologier for CO_2-lagring med betydelig redusert usikkerhet
- Utvidet forståelse av grunnleggende effekter av CO_2-injeksjon på lagringsreservoarer og takbergarter
- Forståelse av effektene av storskala lagring på reservoarene
- iCCS – et verktøy for multi-kriterie vurdering av CO_2 verdikjeder

BIGCCS-forskerne har registrert 657 bidrag i publikasjonsdatabasen CRIStin – 219 av disse var vitenskapelige tidsskriftartikler. Personer knyttet til senteret mottatt *IEA Greenman Award* to ganger, og *SINTEF og NTNU CCS prisen* tre ganger.

Med industrien i fokus

Kontinuerlig fokus på å skape nyttige resultater for industrien har resultert i 46 dokumentert innovasjoner på forskjellige trinn på TRL-skalaen. Forskere vil fortsette å utvikle enkelte av disse videre, mens andre allerede står til disposisjon for industripartnerne. Til syvende og sist er det opp til industrien å ta i bruk disse resultatene.

Den nye generasjonen

Utdanningsprogrammet inkluderte 26 doktorgrader, 8 postdoktorer og 52 masterstudenter med CCS-relaterte emner. Kun én PhD fullførte ikke studiet og bare 10 ekstra måneder var nødvendig for kandidatene samlet. Dette vitner om høy effektivitet. 21 professor var aktive i veiledning av kandidatene. Fire av kandidatene - Christian Eichler, Georg Baumgartner, Sissel Grude, og Chao Fu - fikk spesielle utmerkelser for sitt arbeid.

Internasjonalt ansvar

BIGCCS har bidratt aktivt i utviklingen av europeiske CCS-strategier både innenfor forskning og utdanning. Spesielt involvert har senteret vært i *CCS Joint Program* under *European Energy Research Alliance (EERA JP-CCS)* og den europeiske teknologiplattformen *Zero Emission Fossil Fuel Power Plants (ZEP)*, hvor vi har innehatt ledende stillinger.

SINTEF er koordinator for tre EU-prosjekter med temaer som er relevante til senterets aktiviteter. GATEWAY og CEMCAP (begge Horizon 2020), og IMPACTS (FP7) er alle prosjekter som har bidratt til å styrke BIGCCS sin kompetansebase.

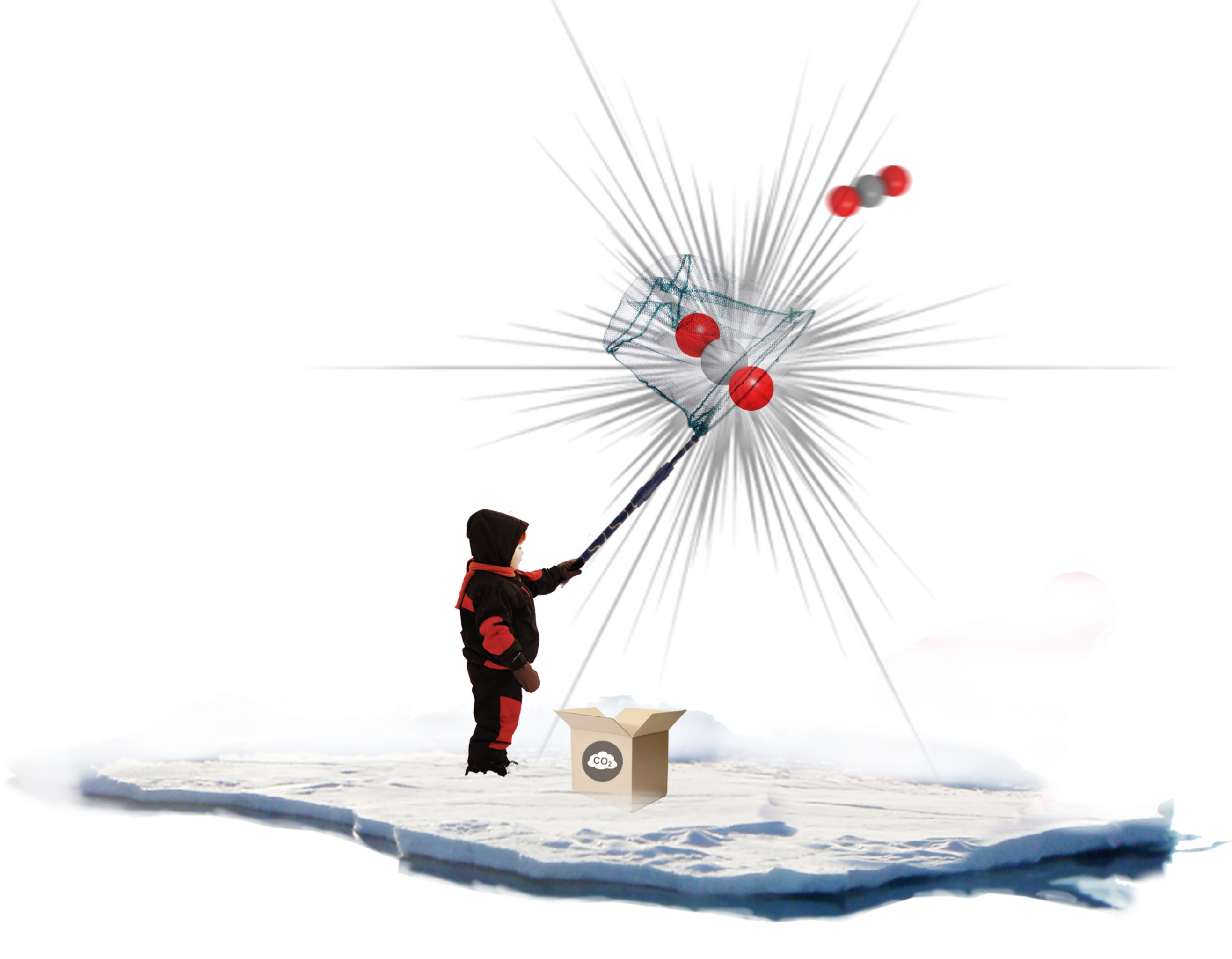
Senteret har samarbeidet nært med *Sandia National Laboratory* og *University of Berkeley*, to av verdens ledende institusjoner innen forbrenningsteknologi. Dette har blant annet resultert i utveksling av forskere.

Det var et aktivt samarbeid mellom BIGCCS og den norske noden i det europeiske initiativet *Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL)*, som er utformet for å gi forskere tilgang til forskningsinfrastruktur viet til CCS-teknologier.

Trondheimskonferansen (TCCS) er en møteplass for CCS-forskere. Konferansen arrangeres hvert andre år og samler nær 400 deltakere fra hele verden. BIGCCS har organisert TCCS tre ganger, i 2011, 2013 og 2015.

Merverdien av et FME senter

Den lange varigheten gir et FME flere fordeler. Den er et utmerket grunnlag for utvikling av nye prosjekter som kan utfylle pågående senter-aktiviteter. Opprettelsen av sterke og varige nettverk - både nasjonalt og internasjonalt - er en annen fordel. Med prosjekter som varer så lenge, vil enkeltpersoner og organisasjoner være villige til å investere mer tid og ressurser for å utvikle varige relasjoner som til slutt kan gi nye muligheter og generere tettere prosjekt-samarbeid. Status som senter betyr også økt synlighet. BIGCCS sine samarbeidspartnere er blitt stadig mer populære som partnere i nye prosjektsøknader. Dette er en verdifull egenskap for fremtiden.



AIMING HIGH – VISION AND GOALS

In the *Climate Agreement* adopted by the Norwegian Parliament in February 2008, CCS is pointed out as one of the important measures in reducing global CO_2 emissions. The BIGCCS Centre was established with a clear vision of contributing to the ambitious targets set out in the *Climate Agreement.* This vision has remained the guiding star for all activities throughout the Centre period.

The overall vision of BIGCCS was to enable sustainable power generation from fossil fuels based on cost-effective CO_2 capture, safe transport, and underground storage of CO_2. To help achieve this, the Centre's specific objectives were to build expertise, close critical knowledge gaps in the CO_2 chain, and develop novel technologies.

In evaluating the achievement of this objective at its last meeting in December 2016, the Board agreed that BIGCCS delivered beyond expectations. It was noted that the knowledge developed was crucial in realizing the Feasibility Study for the large-scale CCS project in Norway. The Board also underlined the value and importance of the networks that BIGCCS built, in respect to the fact that the CCS predicament is too vast to be solved by a single country, let alone a single company.

... crucial knowledge and a basis for technology breakthroughs required to accelerate the development and deployment of large-scale CCS.

In further detail, the tangible objective of the Centre aimed at paving the ground for fossil fuel-based power generation that employs CO_2 capture, transport and storage with the potential of fulfilling the targets of: 90% CO_2 capture rate, 50% cost reduction, and less than 6 percentage points fuel-to-electricity penalty compared to state-of-the-art fossil fuel power generation. Calculations and experiments conducted over the last eight years confirm that all of these goals are well within reach.

Scientifically, the Centre provided crucial knowledge and a basis for technology breakthroughs required to accelerate the development and deployment of large-scale CCS. This was accomplished through dedicated, long-term, targeted basic research of high scientific quality, professional management, and international partner involvement. In other words, the knowledge is available and waiting to be used.

BIGCCS fostered innovation and value creation within CCS technologies along the whole CO_2 value chain. The basis for new services and products for the user partners ranged from novel separation technologies to value creation from transport and storage on the Norwegian Continental Shelf. By the end of the centre period, BIGCCS had registered and documented 46 innovations, several of them ready to be taken to the market by industry.

The Centre aimed to educate 18 PhDs, eight post-docs, 50 MSc graduates, and finished with 26 PhDs, eight post-docs, and 52 MSc graduates. It is worthwhile to note that only one PhD candidate dropped out, and that five PhD candidates needed a total of 10 months extra time. That must be close to a record.

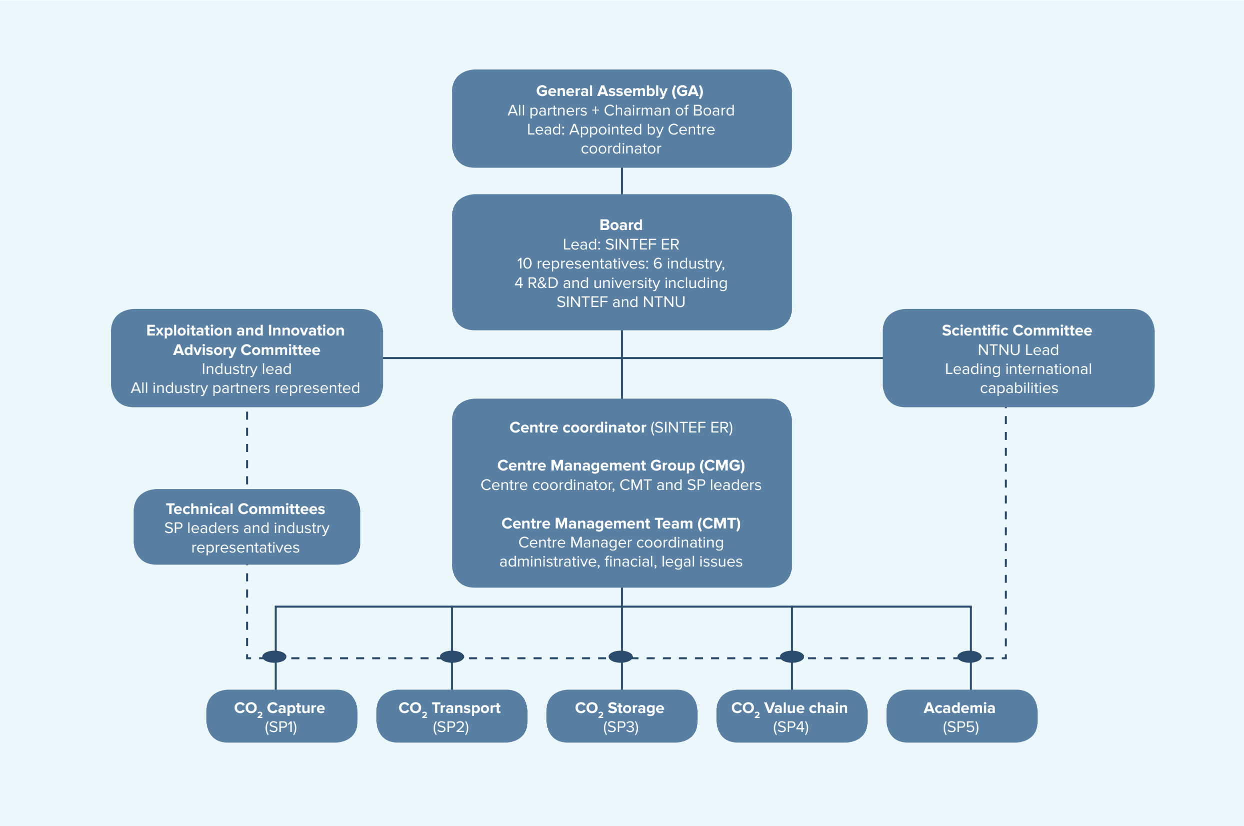
One area in which expectations were not met was in gender distribution. The goal was a 50-50 gender split, whereas there were only 24% women in the PhD/post-doc group and 38% women among MSc candidates. Future endeavours will include efforts to increase the recruitment of women.

BASIC FACTS

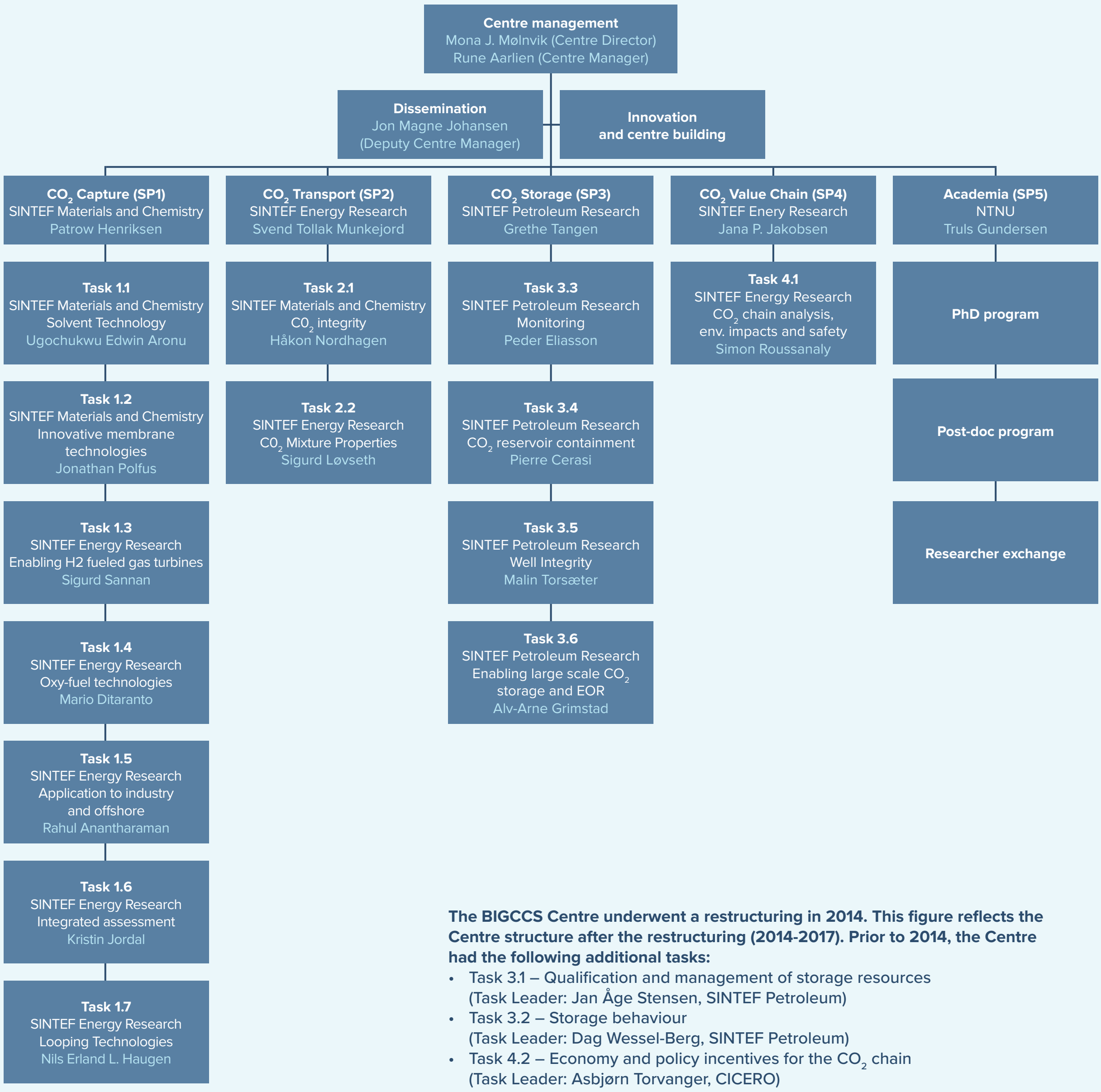
The idea behind a grand coordinated R&D effort in CCS was developed by Dr. Inge Gran in the late 1990s. At the turn of the century, the report "Power generation with CO_2 capture and sequestration – R&D needs" was presented to the Norwegian Research Council program Klimatek (later to become Climit). Funding was secured for a CO_2 strategic institute program (SIP) and a knowledge development project (KPN), both started in 2001. A second KPN started in 2004 was merged with the first KPN, and after adding a user interest group, this became the *BIGCO2 phase I* project (2004-2006). This project was then continued as *BIGCO2 phase II* (2007-2011), which was the foundation for the BIGCCS project. Central in the early development phase of the BIGCCS project (2009-2017) were Grethe Tangen and Nils A. Røkke.

Organization – Centre structure

The BIGCCS Centre covered the entire CO_2 value chain, including capture, transport, and storage. Each of these key CO_2 chain elements were captured in the governance structure (below) as sub-programs (SPs). Sub-program "CO_2 Value Chains" optimized alternative CO_2 chains, and the "Academia" sub-program coordinated the educational activities.



BIGCCS governing structure.



The BIGCCS Centre underwent a restructuring in 2014. This figure reflects the Centre structure after the restructuring (2014-2017). Prior to 2014, the Centre had the following additional tasks:

- Task 3.1 – Qualification and management of storage resources (Task Leader: Jan Åge Stensen, SINTEF Petroleum)
- Task 3.2 – Storage behaviour (Task Leader: Dag Wessel-Berg, SINTEF Petroleum)
- Task 4.2 – Economy and policy incentives for the CO_2 chain (Task Leader: Asbjørn Torvanger, CICERO)

BIGCCS work breakdown structure.

CMG – Managing operations

The Centre Management Group (CMG) was responsible for the day-to-day operations of the Centre. Its operations were guided by the Board and the annual working plans. The group consisted of the leaders of the five sub-programs, Centre Director Mona Mølnvik, Project Manager Rune Aarlien, and Operations Manager Jon Magne Johansen. The SP leaders were: Partow Henriksen – Capture (SINTEF Materials and Chemistry), Svend Tollak Munkejord – Transport (SINTEF Energy Research), Grethe Tangen – Storage (SINTEF Petroleum Research), Jana P. Jakobsen – Value Chains (SINTEF Energy Research), and Truls Gundersen – Academia (NTNU). The CMG met every second week throughout the Centre period, and functioned as a professional decision-making body.

BIGCCS Centre Management Group


Mona J. Mølnvik


Truls Gundersen


Jon Magne Johansen


Partow P. Henriksen


Svend Tollak Munkejord


Grethe Tangen


Jana P. Jakobsen


Rune Aarlien

BIGCCS Task leaders


Ugochokwu Edvin Aronu


Jonathan Polfus


Sigurd Sannan


Mario Ditaranto


Rahul Anantharaman


Kristin Jordal


Nils Erland Haugen


Håkon Ottar Nordhagen


Sigurd Weideman Løvseth


Peder Eliasson


Pierre Cerasi


Malin Torsæter


Alv-Arne Grimstad


Simon Roussanaly

ExCo meeting hosted by Engie in Paris on May 20, 2014. From left: Mona Mølnvik (SINTEF), Rune Teigland (TOTAL), Ole Lindefjeld (ConocoPhillips), Svein Solvang (Gassco), Nils Røkke (SINTEF), Tom Steinskog (Engie), Ole Kristian Sollie (Shell), Rune Bredesen (SINTEF), Åse Slagtern (Research Council of Norway), Britta Paasch (Statoil), Hallvard Svendsen (NTNU), Kristin Jordal (SINTEF).

Board – Overseeing operations

The main responsibility of the Board was to oversee the operations of the Centre, approve the annual working plans, and give guidance to the CMG. All industry partners held a seat on the Board, while research partners alternated. To strengthen contact with industry, board meetings were held at the location of most user partners. Chaired by Nils A. Røkke throughout the Centre period, the Board met twice every year.

The ultimate decision making body in the Centre was the General Assembly (GA), on which all partners held a seat throughout the period. The GA met once every year to verify that the Board performed its duties according to the consortium agreement. Chairs of the GA were elected at each meeting, with Ms. Pascale Morin (TOTAL) and Mr. Ole Kristian Sollie (Shell) serving more than once.

Partners

The following companies were partners (the period is given for those not having been partners throughout the centre period): Aker Solutions (2009-2012), ConocoPhillips (2009-2014), Engie (2010-2017), Gassco, Hydro (2009-2012), DNV (2009-2012), Shell, Statkraft (2009-2010), Statoil, and TOTAL E&P Norway.

The research partners in BIGCCS were: British Geological Survey, CICERO (2009-2013), Deutsches Zentrum für Luft- und Raumfahrt, Geological Survey of Denmark and Greenland, Geological Survey of Norway (2009-2013), NTNU, NTNU Social Research (2009-2014), SINTEF Energy Research (Host Institution), SINTEF Materials and Chemistry, SINTEF Petroleum Research, Technische Universität München and University of Oslo.

BIGCCS cooperated with a number of associated partners not formally partners of the Centre. An overview of the most prominent is given in chapter 8, International Cooperation.

Scientific Committee

Headed by Professor May-Britt Hägg, the Scientific Committee gave strategic advice to the Centre by

BIGCCS Scientific Committee. Top: Alan Kerstein, Forman A. Williams, Matthias Wessling, Per Morten Schiefloe. Bottom: Gary T. Rochelle, Sally Benson, Susan Hovorka, May-Britt Hägg.

evaluation of scientific performance. The Committee consisted of world-class experts covering the entire CCS value chain. Members were: Alan Kerstein (Sandia National Laboratories, USA), Forman A. Williams (University of California at San Diego, USA), Matthias Wessling (University of Twente, Netherlands), Per Morten Schiefloe (NTNU Social Research, Norway), Gary T. Rochelle (University of Texas at Austin, USA), Sally Benson (Stanford University), Susan Hovorka (University of Texas at Austin, USA), May-Britt Hägg (NTNU Chemical Process Technology, Norway).

Cooperation within the Centre – Binding the Centre together

Close cooperation between research and user partners has been a priority in BIGCCS. The Centre organised annual consortium days and annual meetings for the different sub-programs, both with substantial participation from industry.

Having Board meetings combined with workshops at user partner's locations gave researchers the chance to interact with researcher colleagues in industry. These meetings typically had high attendance from the industry representatives.

Dedicated technical meetings were staged regularly by the individual BIGCCS tasks. Such events were held both as physical meetings and as telephone conferences. Owing to increasing travelling restrictions within industry companies, telephone conferences were preferred.

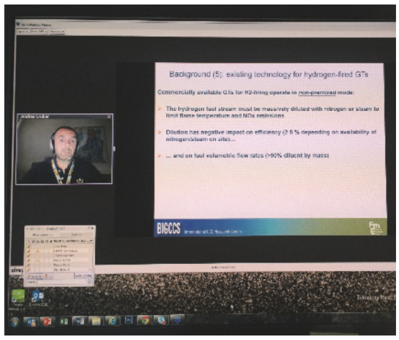
In terms of industry attendance, the webinar series held during the spring of 2016 was a particularly successful platform for cooperation. All 14 of the BIGCCS tasks held a webinar, with industry members given the chance to suggest topics. The series had almost 300 registrants, about half of which came from user partners.

Did you know?

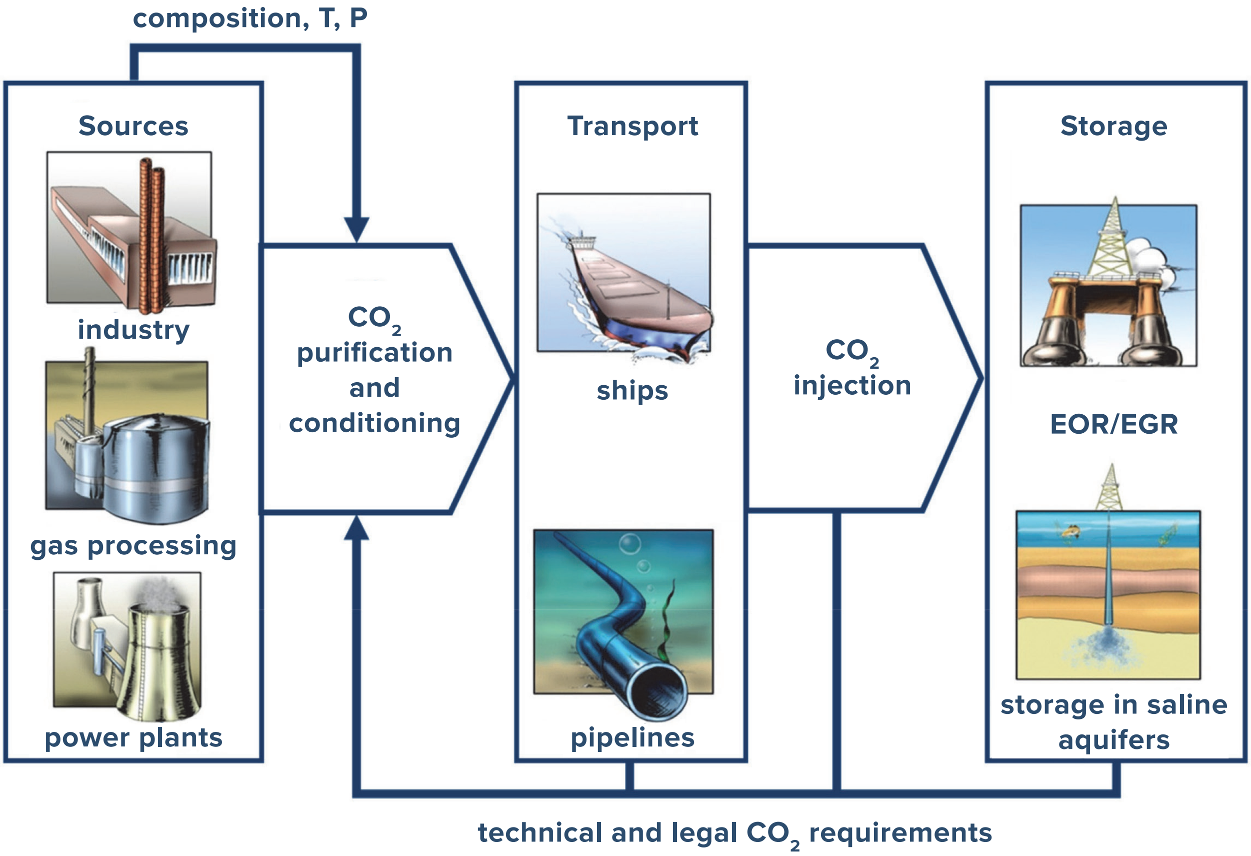
Did you assume that the "BIG" in BIGCCS is an effort so say something about the size of the project? Well the scope of BIGCCS was indeed big, but that's not what it meant. The BIG acronym actually comes from the Norwegian word "**B**ruker-**I**nteresse**G**ruppe", which translates into English as "user interest group".

A Consortium Day meeting in Trondheim, May 22-23, 2015.

Workshop with Engie in Paris on May 21, 2014.



Screenshot of webinar held by Andrea Gruber on May 13, 2016.



The BIGCCS Centre covered the entire CO_2 value chain.

FINANCING OF THE CENTRE

Summary sheet

	CONTRIBUTOR	CASH	IN-KIND	TOTAL
FME BIGCCS (core)	Host institution (SINTEF Energy Research)		21 441 931	21 441 931
	Research partners		72 101 230	72 101 230
	Companies	121 500 000		121 500 000
	The Research Council of Norway		160 000 000	160 000 000
	The Research Council of Norway infrastructure		15 300 000	15 300 000
Affiliated KPN* projects ** (Research Council of Norway/CLIMIT R&D)	CO_2MIX	26 000 000		26 000 000
	BIGCLC Phase II	21 600 000		21 600 000
	CAMPS	12 000 000		12 000 000
	FEFRock	9 600 000		9 600 000
	BIGCLC Phase III	14 500 000		14 500 000
	HyMemCOPI	7 000 000		7 000 000
	SINTERCAP	7 200 000		7 200 000
	Well intergrity	7 200 000		7 200 000
	uniCQue	6 400 000		6 400 000
	Total			**501 843 161**

** Competence building project with user involvement.*
*** Full project titles in appendix (p. 57).*

RESULTS – KEY FIGURES

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Scientific publications (peer reviewed)	1	11	13	35	26	40	34	16		**176**
Dissemination meassures for users	12	66	35	64	61	93	117	91		**539**
Dissemination meassures for the public		12		2	1	3	10	18		**46**
New/improved methods/models/ prototypes finalised		2	4	7	5	11	8	4		**41**
New/improved products/processes/ services finalised				1			4			**5**
PhD degrees completed*			1	1	3	9	5	2	3	**24**
Post doctoral researchers			1	1	2	2		1	1	**8**
Master degrees		7	13	9	11	6	6			**52**

** Two PhDs are remaining. One will finish late 2017/early 2018, and one in 2018 (owing to late start).*

More details can be found in the appendix section.

HYDROGEN FROM FOSSIL FUELS

An increased use of hydrogen with CCS technology may prove essential to meet climate goals and achieve a sustainable future.

BY DAVID NIKEL

Limiting the global temperature increase to no more than 1.5°C as per the Paris Agreement will require global efforts to substantially reduce CO_2 emissions. With this goal in mind, combining hydrogen production from fossil fuels with CCS technology could be an important transition in a move towards a sustainable future.

Hydrogen offers a long-term potential for energy systems with almost zero emissions.

Hydrogen offers a long-term potential for energy systems with almost zero emissions. Hydrogen-rich gases can be synthesized from fossil fuels in power plants with pre-combustion CCS. Hydrogen can also be generated by localized and renewable energy sources and used as a convenient energy storage medium.

Hydrogen production with CO_2 capture

Based on BIGCCS research, the paper 'Hydrogen Production with CO_2 capture' was published in the International Journal of Hydrogen Energy. It provides an overview of the different technology options that are readily available as well as under development for hydrogen production combined with CCS.

With courtesy of Kawasaki Heavy Industries, Ltd.

Few technologies exist that can produce both high-purity hydrogen and CO_2 at transport quality simultaneously. Producing hydrogen from fossil fuels, while capturing the CO_2 for transport and storage is therefore a matter of matching hydrogen and CO_2 separation technologies in a best possible manner, considering the planned transport option for the CO_2 and the way in which the hydrogen will be used.

Hydrogen production with CO_2 capture can potentially lead to large CO_2 emission reductions in sectors such as the transport sector. Currently, road transport makes up almost one quarter of all global CO_2 emissions. Increased use of electric cars and hydrogen-powered fuel cell cars are the main ways to significantly reduce this amount.

"We believe the paper's contents are even more relevant after the Paris Agreement," says Kristin Jordal, Senior Research Scientist at SINTEF Energy Research. "It is our hope that this review on methods for production and purification of hydrogen from fossil fuels can stimulate further research on and development of technologies for low-emission hydrogen production."

Hydrogen combustion technologies

Hydrogen is characterised by peculiar physical properties compared to more conventional gaseous fuels, as natural gas. Technological challenges need to be overcome if high efficiency and low emissions must be safely achieved when scaling up power output. BIGCCS addressed two of the most critical aspects related to hydrogen combustion in gas turbines in collaboration with Sandia National Laboratory and the German Aerospace Center, along with PhDs at the Technical University of Munich and the University of California Berkeley.

Positive results ranged from an improved understanding of the physics, to the creation of engineering scaling laws, to the development of innovations, explains Andrea Gruber, Senior Research Scientist at SINTEF Energy Research:

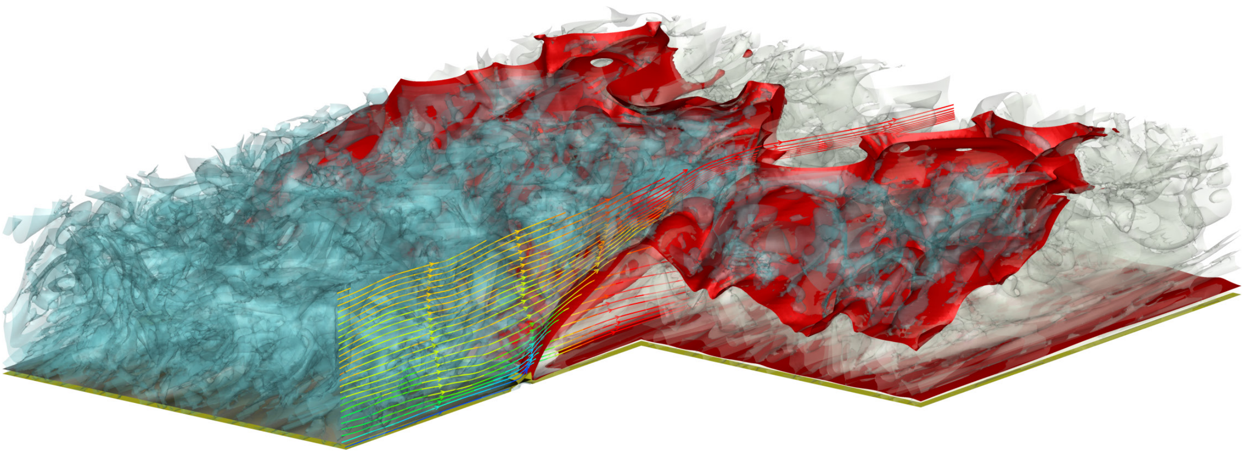
“A previously unknown fundamental feature of flame propagation, resulting from an intricate interaction between near-wall turbulence and flame front shape, was discovered and its role in relation to the occurrence of flashback - an undesired flame displacement upstream from its design position - was explained.”

“Also, a new set of engineering criteria for gas turbine burner design was determined, and an innovative fuel injection concept was proposed for hydrogen-fired gas turbines.”

Design of membrane processes

The integration of hydrogen-separating palladium membranes and low-temperature CO_2 separation into coal gasification plants with CO_2 capture was investigated. The purpose was to design a self-sustained hybrid process that can produce the power required for CO_2 capture as well as for hydrogen liquefaction.

Dense inorganic membranes for pre-combustion CO_2 capture were systematically studied. Membrane materials were developed, and upscaled membranes were fabricated and tested in realistic operating conditions for pre-combustion steam methane reforming.



"Visualization of computational results from high-resolution Direct Numerical Simulation (DNS) performed in collaboration with Sandia NL - A turbulent, strongly-wrinkled hydrogen flame (marked by the red surface) propagates from right to left against the main flow direction (visualized by streamlines) in the wall boundary layer of the combustor liner. The reactants' mixture of hydrogen-air (cyan-colored region) is highly reactive and its expansion due to the temperature increase in the products (white-colored region) is able to generate a flow reversal just ahead of the flame leading edge, thereby facilitating the upstream propagation of the whole flame front."

A POSITIVE START TO CHEMICAL LOOPING TRIALS

A new chemical looping combustion technology for CO_2 capture was successfully tested at a 150kW pilot plant in Trondheim.

BY DAVID NIKEL

Reducing the cost and complexity of CO_2 capture will remove a big barrier to the wider commercial adoption of CCS. The combustion of gas, oil, coal, biomass and waste used to produce power, heat and steam generates CO_2.

The challenge of separating CO_2

Typically, CO_2 is separated using post-combustion separation, or by using oxy-combustion technology. In traditional single stage combustion, the release of a fuel's energy occurs in an irreversible manner.

A new chemical looping combustion technology for CO_2 capture was successfully tested at a 150kW pilot plant in Trondheim.

The Chemical Looping Combustion (CLC) approach splits the combustion process into two by means of an air and a fuel reactor. At a normal operating temperature of 850°-950°C, a metal oxide is employed as a bed material providing the oxygen for combustion in the fuel reactor. The reduced metal is then transferred to the air reactor, re-oxidized, and reintroduced into the fuel reactor completing the loop.

In theory, this technique allows a CLC-enabled power station to approach the ideal output for an internal combustion engine without exposing components to excessive working temperatures. The oxidiser exit gas can be safely discharged to the atmosphere, as the reducer exit gas contains almost all the CO_2 generated by the system. Water vapour can easily be removed from the second flue gas via condensation, leaving a stream of almost pure CO_2 remaining.

A successful experiment

Development of CLC technology has been conducted at several research centres in Europe, USA, China and Korea. The 150kW facility at Tiller (Trondheim) is among the largest at a height of 7 metres.

The design of the reactor and solutions were chosen to reflect real industrial conditions, thus enabling an easier transition to a larger-scale demonstration plant. The fuel reactor is designed as a circulating fluidized bed operating in fast fluidization mode, leading to high

Project leader Øyvind Langørgen inspecting the installation of the CLC rig gas-solid mixing throughout the reactor volume. This is different from most other CLC test reactors that use bubbling fluidized bed fuel reactors.

A one-day experiment at Tiller comprised a heat-up sequence, operation in CLC mode and a shut-down sequence. The oxygen carrier material was a copper-oxide based material impregnated on a γ-alumina support. Particle density was low compared to the reactor design value causing a limitation on the maximum fuel power.

At about 100kW, the performance was very good. During the last hour, constant operating conditions were maintained and the system showed a stable performance with a high degree of methane conversion, up to about 98%.

The 150kW rig has also put SINTEF in the position to be a partner in CLC projects on pilot testing in real conditions, such as with the ongoing EU FP7 project "SUCCESS" and the Nordic Energy Research project "Negative CO_2".

Predicting the behaviour

An interconnected reactive CFD model has been developed and implemented in-house. The work provides a numerical tool with the capability to simulate both the hydrodynamics and the reaction kinetics of the CLC reactor system. This is an important step towards the understanding and commercialization of this capture technology.

From the assembly of the CLC rig.

USING DATA TO AVOID PIPELINE FRACTURES

Mathematical models are helping to envision the pipeline design of a CCS-enabled future.

BY DAVID NIKEL

When CCS is deployed at full-scale, large quantities of CO_2 must be transported from the capture plants to the storage sites. Although CO_2 has been transported in pipelines since the 1970s, such solutions aren't suitable for a much larger-scale implementation.

And large-scale it will be, if the current IEA two-degree scenario is to be believed. It estimates an annual requirement to move six billion tonnes of CO_2 by 2050. That's around 80 times larger than today's annual export of natural gas from Norway.

"These first results are very promising, and we think that the model can be employed to develop engineering tools valid for CO_2 transport pipelines,"

Creating a safe design is more complicated than for a typical hydrocarbon pipeline because of the non-linear thermodynamic properties of CO_2. To achieve the transport of such large quantities in a safe manner, it is necessary to perform accurate calculations on the behaviour of CO_2 with impurities during conditioning, transport by pipeline or ship, and injection into the storage reservoir.

"CO_2 transport is feasible and generally safe," explains Svend Tollak Munkejord, Chief Scientist, Gas Technology at SINTEF Energy Research. "But if full-scale CCS were to be deployed today, conservative design and operational decisions would have to be made due to the lack of quantitative validated models. Such models require data that is lacking today, but we have developed accurate laboratory facilities for some of the required data," says Munkejord.

Avoiding running-ductile fractures

One area of focus for BIGCCS was on how to avoid the severe damage to a pipeline that could trigger a running-ductile fracture. Although a rare occurrence, it is something that must be taken into account in all pipeline design work.

"Damage due to third-party impact or corrosion could cause a running-ductile fracture. The phenomenon is similar to what happens when you cook a sausage too fast. Boiling it instead of simmering it can cause it to simply crack open," says Munkejord.

Although semi-empirical engineering tools called two-curve methods have been used in natural gas pipelines since the 1970s, they are not suitable for newer, tougher steel. Nor are they suited for the transport of CO_2, which has significantly different properties from natural gas.

The BIGCCS Centre took a cross-disciplinary approach to include more physics into the models in order to achieve greater predictive capability.

A unique model useful for industry

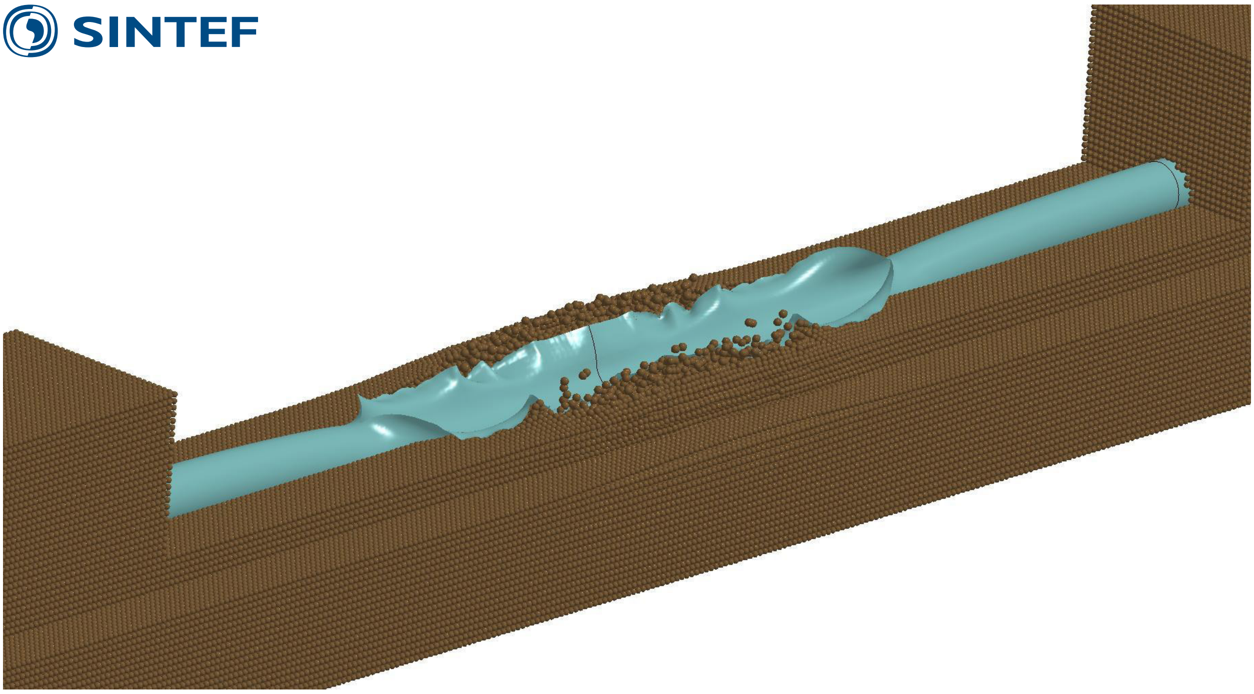
The resulting model combines advanced thermo-fluid dynamics with material and fracture mechanics. The internationally unique model includes the complex two- and three-phase (gas-liquid-solid) decompression behaviour of CO_2 and CO_2-rich mixtures, and features direct physical coupling between the fluid and the structure.

As BIGCCS featured such strong industry collaboration, the team took care to create a model that would be simple to use outside of the academic environment. The model was validated using the little experimental data that exists on running-ductile fractures in pipelines pressurized with methane, hydrogen, pure CO_2 and a CO_2-nitrogen mixture. Simulations show how the CO_2 exerts higher forces on a larger area of the pipe than natural gas does.

"These first results are very promising, and we think that the model can be employed to develop engineering tools valid for CO_2 transport pipelines," says Munkejord. "This is important since it contributes to reducing the cost of CCS while assuring the public that safety is high. The models can also be applied to other parts of the CCS chain where dynamic events must be taken into account, such as ensuring integrity of CO_2-injection wells."

The consortium of the CO_2Pipetrans project led by DNV GL allowed the use of their crack-arrest experimental data for CO_2 pipelines for model validation.

"This was of great importance, since the confidence in a validated model is much higher," says Munkejord, whose team were invited to collaborate with MIT and the University of Regensburg on coupled fluid-structure modelling of running-ductile fractures.



Visualization of a simulated running ductile fracture in a CO_2 pipeline II

REDUCING LEAKAGE FROM WELLS

Cement is a key factor in leakage from CO_2 wells.
Its degradable qualities mean it must be a focus throughout the lifecycle of the well:
From design and construction to permanent plugging.

BY DAVID NIKEL

For long-term CO_2 storage to become a viable industrial option, wells must remain leak-free. Their quality will determine for how long CO_2 remains imprisoned in deep subsurface reservoirs. But avoiding leaks while using degradable materials like steel and cement on what is essentially a man-made piercing into a naturally-sealed CO_2 storage reservoir is a major challenge to overcome.

The work on well integrity within BIGCCS has revealed in more detail how, when, why and where leaks develop in CO_2 wells.

Plugging the holes

It is still unknown how long cement lasts in the highly pressurized and hot subsurface. That poses a significant problem for well plugging, a process where cement is pumped into an expired well to trap fluids inside. But it's not just CO_2 that can leak from abandoned wells. Methane – which is many times worse for the climate than CO_2 – can also escape.

During BIGCCS, a new code for simulating cement placement in wells was created.

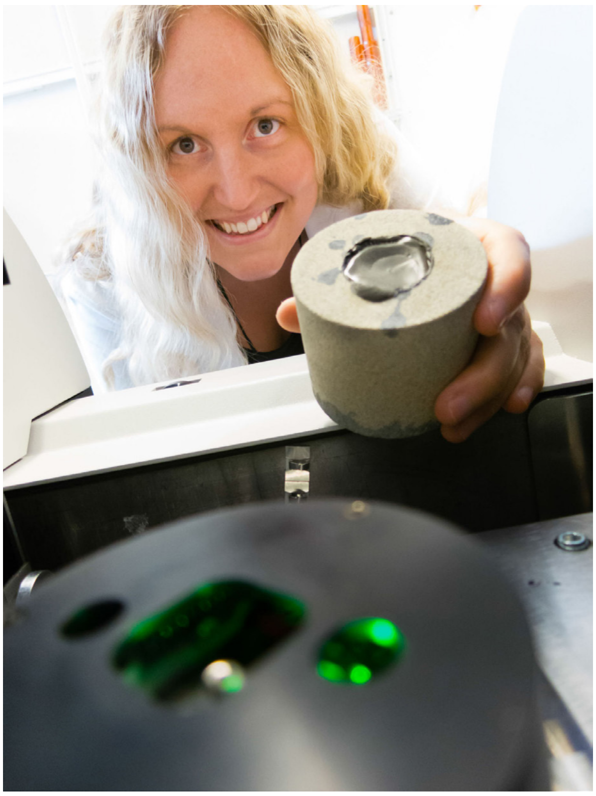
In a 2010 study published in the Proceedings of the National Academy of Sciences, researchers found that abandoned wells in the US state of Pennsylvania may have contributed 4 to 7 percent of the total man-made methane emissions from all sectors.

BIGCCS research has developed new ways of estimating the lifetime of various plugging materials in the harsh CO_2 well environment. A methodology for how to calculate the CO_2 leakage rate that can occur through well defects has also been developed.

In some circumstances, CO_2 leakage has been found to be self-limiting, since leakage paths close up due to precipitation. This is good news for CCS, and suggests that the possibility for using CO_2 for well remediation should be further explored.

Improving cement placement and bonding quality

The problems observed with expired wells is often due to inappropriate well construction. The further down into the earth you drill, the higher the pressure and therefore the harder it becomes to stabilize the rock walls to avoid collapse. Typically, steel pipes are cemented into the borehole to maintain integrity, leading to a telescopic structure of cemented pipes of different diameters within any one well. For the wells to be leak-free the cement must fill all the available



Malin Torsæter.

space into which it is pumped, and it must bond well to its surroundings.

During BIGCCS, a new code for simulating cement placement in wells was created. This is of great importance for safe CO_2 storage, since poor cementing is a major reason for loss of integrity in wells today. To encourage the usage and improvement of the code, it has been created on an open-source basis. This allows anyone to use the code, and to improve the code. It is hoped this decision will lead to the code becoming a valuable addition to the commercial and proprietary codes owned and used by service companies.

If cement does not bond properly to rock or casing steel, leakage paths can form at its interfaces. New methods for studying and quantifying cement bonding quality have been applied to map cement bonding to a range of rock and steel types, and to study the impact of cement additives, drilling fluids, filter cakes and even electric field (see figure below). The resulting "encyclopaedia" of cement bonding properties can be a useful reference for material- and fluid choices during construction of future CO_2 wells.

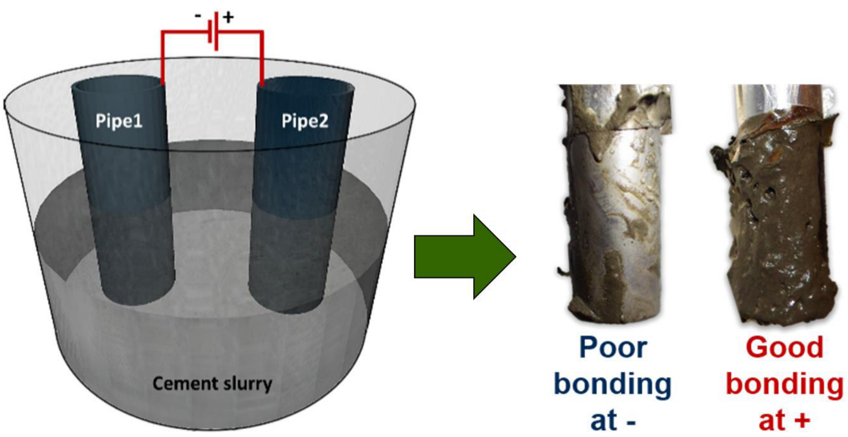
Safer CO_2 injection wells

It must be expected that temperature and pressure variations occur in CO_2 injection wells because of, for example, on/off injection of cold CO_2 or well shut-in periods during intervention or repair. BIGCCS research examined the effect of temperature variations on well integrity, and also the effect of low probability events like a CO_2 blow out. The results provide "safe temperature windows" and recommended injection schedules for CO_2 wells, and give advice on material and fluid selection for enhancing well robustness.

... it has been created on an open-source basis.

Task leader Malin Torsæter says: "Our work has been closely followed by industry, so much so that of the 42 attendees of our webinar on CO_2 well integrity, 31 were from industry. International interest in the work has been strong, with invited presentations given at the American Geophysical Union Fall Meeting and the Offshore North Sea (ONS) conference."

Our work has been closely followed by industry



In a SINTEF experiment, steel casing pipes with positive and negative voltage were immersed in cement slurry. This was found to strongly affect cement-steel bonding, which was improved with positive voltage. The novel concept has potential to minimize leakage paths at the cement-steel interface in wells, and thus enhance safety of CO_2 storage.

HELPING INDUSTRY TO TACKLE UNCERTAINTY

A BIGCCS tool helps industry and policy-makers to analyse options and make better decisions.

BY DAVID NIKEL

One of the main roadblocks for large-scale implementation of CCS by industry is the need to convince investors and other stakeholders that an investment in a CCS project will pay off in both the short and long run.

BIGCCS researchers developed a CCS value chain tool called iCCS to perform multi-criteria assessment and analysis of the whole CCS chain, including technical, cost and environmental factors. The tool has been tested in multiple scenarios and been shared with the centre's industrial partners.

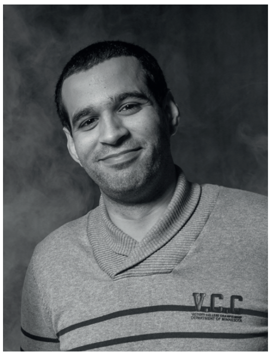
The initial interest from our partners started very early. They were very active, asking questions about how the model works and how they could apply it to their cases

Each element in the CCS chain is often optimised separately considering just some elements of the whole CCS value chain. However, decisions made at one stages can affect the other parts of the chain resulting in uncertainties and cost which may be higher than the over cost-optimal chain. The iCCS methodology integrates and optimises the entire chain as one system to help unlock hidden cost savings.

Interest from industry and beyond

When task leader Simon Roussanaly started receiving questions from industrial partners, he knew he was on to a good thing. "The initial interest from our partners started very early. They were very active, asking questions about how the model works and how they could apply it to their cases," he says.

Simon explains there is a wide range of groups that could benefit from the methodology and tool, including one notable group outside of industry.



"It can help potential CCS infrastructure owners or customers select the most cost-effective options for CCS deployment, while for technology providers and engineering companies it can highlight the need for technology improvements and measures to promote the CCS technology. Outside of industry, the tool could be used by policy-makers to assess the effects of policy options and global market scenarios on the CCS chain economy."

From idea to working tool

In 2016, the tool was shared with the BIGCCS industrial partners through a series of workshops to ensure a smooth transmission. Getting to this point however, took a lot of work and a lot of input from industry partners. Several case studies were conducted through the development process to validate the tool and demonstrate the methodology to industry partners.

"We published a paper on CCS in transport that involved evaluating more than 400,000 different CO_2 transport chains. The analysis of the impact of different complex pipeline and shipping options would have been impossible to achieve without such a tool," says Roussanaly.

Another case study focused on the cost of capturing CO_2 from a coal-fired power plant. In this situation, CO_2 emissions fluctuate over both the short-term and long-term, and change with the installed capture capacity. The results that were obtained illustrated that by installing a capture capacity capturing the baseload CO_2 emissions, the capture cost could be divided by a factor of three.

Membrane based CO_2 capture

During the development of the tool, a new methodology for design and optimization of membrane-based CO_2 capture was developed, resulting in more cost-efficient processes.

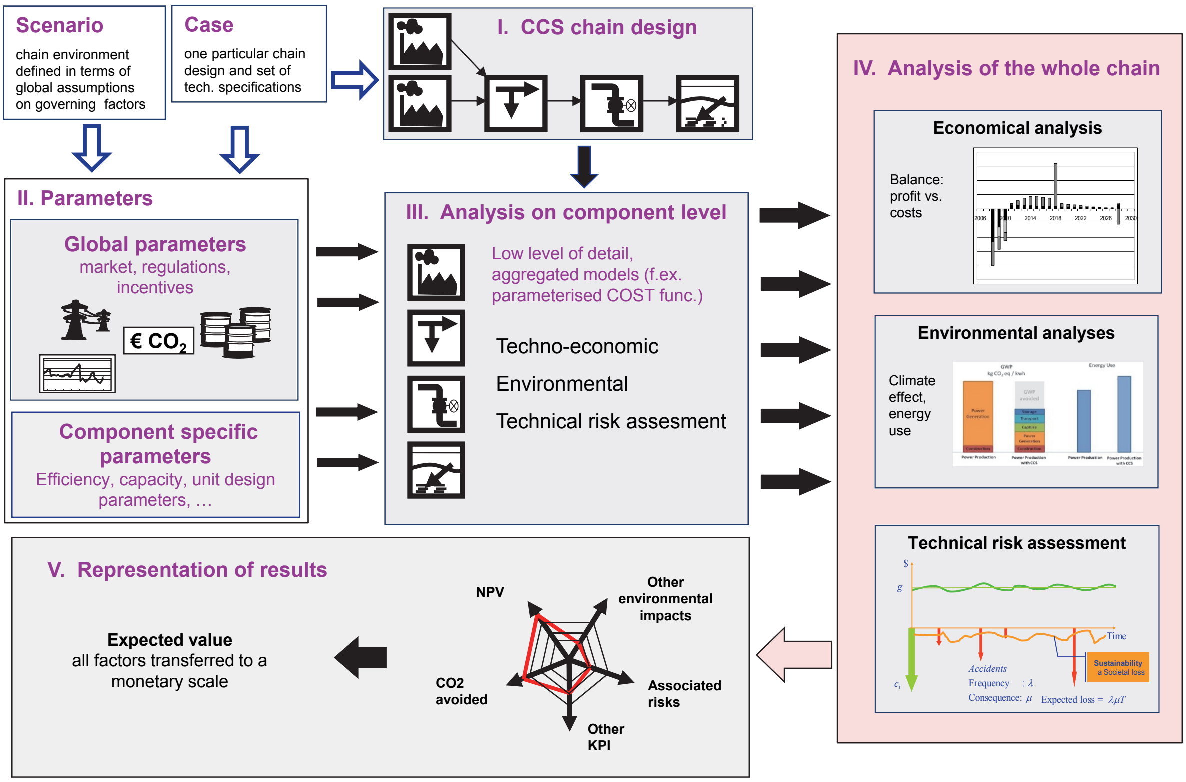
The "attainable region approach" was developed by Karl Lindqvist, Rahul Anantharaman, and Simon Roussanaly from SINTEF Energy Research and illustrated in a collaborative work with Carnegie Mellon University (CMU). A collaboration that is set to continue beyond BIGCCS.

The new module was used to identify the membrane properties required for membrane processes to be cost-competitive with MEA-based post-combustion CO_2 capture from a coal power plant. The impact of different uncertainties such as maturity and membrane cost were investigated and the results were put in the context of membrane development. The results of the collaboration were presented at the 2015 Pittsburgh Coal Conference and GHGT-13, and feedback from the conference participants, BIGCCS partners, as well as the wider CCS and membrane communities has been extremely positive.

Moving forward: Cutting cost and further research

There are three main ways to cut the cost of CCS: Through improved technology such as better solvents and membranes, development of new and innovative technologies, and the smart design and operation of CCS chains. Although the value chain activity focused on the latter, the evaluation tools and methodologies help to evaluate the potential of new or improved technologies in cutting the cost of implementing CCS solutions in industry.

These activities led to three spin-off projects with a combined budget of 18 million Norwegian kroner: The CEPONG projects looking at Clean Electricity production from Natural Gas (two Gassnova/CLIMIT Demo projects) and PilotCCS looking at CCS from a pre-combustion power plant in the Czech Republic (EEA grants). In addition, this activity has been highlighted by BIGCCS partners and is set to be further developed in the new FME NCCS (Norwegian CCS Research Centre), and other national and international projects.



The various elements in the iCCS value chain analysis tool.

OTHER RESEARCH HIGHLIGHTS

BY DAVID NIKEL

CO_2 Capture

New solvent technology

Precipitating phase change solvent systems have the potential to further drive down the cost of CO_2 capture, and are now a step further towards a large-scale implementation.

As natural gas is projected to be the dominant fossil fuel for power generation by 2040, it remains a critical area to research.

Developed during BIGCCS, Novel Precipitating Solvent Systems (NPSS) offers possibilities for lower capture cost through its lower regeneration heat demand and potentials for higher pressure CO_2 recovery. It also gives possibilities for industry waste heat utilization and has a less complex precipitating capture process, because the NPSS has high CO_2 absorption rate even at the precipitating region.

Dynamic modelling of post-combustion processes

The development of a dynamic process model in MATLAB for absorption based CO_2 capture plants gives the possibility to monitor their behaviour at transient conditions. Based on initial work from the BIGCO2 project, the process model was successfully validated by experimental dynamic tests, and used as a stand-alone tool in a simulation study to determine the time constants for the process flow at the pilot plant in Tiller, near Trondheim.

Oxy-fuel capture technology

When BIGCCS began, research in oxy-fuel combustion for Natural Gas Combined Cycle (NGCC) power plants was scarce, because of the higher CO_2 footprint of coal-fired plants. As natural gas is projected to be the dominant fossil fuel for power generation by 2040, it remains a critical area to research.

A major achievement was the construction of the high pressure oxy-fuel combustion facility HIPROX (ECCSEL-funded), which today allows to test oxy-fuel combustion at an industrial relevant scale with a capacity up to 10 bar and 100 kW. An in-house swirl stabilized oxy-burner has been designed and tested at the HIPROX full capacity showing good flame behaviour. The burner study also highlighted and quantified how important is the CO emissions challenge in oxy-fuel combustion. An oxy-fuel demo plant (DEMOXYT) based on retrofitting a gas turbine has been initiated as a research infrastructure under ECCSEL.

The challenge for NGCC is the low CO_2 concentration in the exhaust. Exhaust gas recirculation (EGR) was studied as a concept to improve the efficiency of post-combustion capture in NGCC plants, and a new concept was proposed to implement EGR in pre-combustion capture power cycles as a mean to circumvent the issues of high NO_x emissions from hydrogen-fired gas turbines.

Innovative membrane technologies

Much work focused on the development of dense inorganic membranes to be integrated in pre-combustion decarbonisation and oxy-fuel power generation cycles for CO_2 capture. Hybrid polymeric membranes for post-combustion CO_2 capture in power plants and industry were also developed.

Highlights included:

- Up-scaled fabrication procedures and facilities for ceramic membranes. The development and optimisation of the whole fabrication process from powder conditioning, paste and slurry preparation, extrusion of the membrane support, coating of the membrane layer and firing in several stages.
- Ceramic membrane material development. In particular, the relationship between hydrogen permeation through the membranes, and hydrogen production by water splitting on the sweep side.
- Hybrid polymeric-inorganic membranes for CO_2 separation - The influence of amine-POSS® nano-particles dispersed in a polyvinyl alcohol (PVA) matrix was investigated. Duration tests in the presence of up to 400 ppm SO_2 showed that SO_2 does not have a permanent negative effect on the membrane performance.

CO_2 Transport

The CO_2 mix

The CO_2Mix project was established to address the need to improve the data situation for CO_2-rich mixtures. The main objective was to acquire accurate experimental data on thermophysical properties of CO_2-rich mixtures at operational conditions, and to use this data to improve and extend the range of validity of existing thermodynamic models.

Parameter fitting was performed to validate the new data, and binary interaction parameters of existing models were provided. Limitations with existing models applied to CCS mixtures were identified. This work provides a good platform for future optimisation of the design and operation of CCS systems.

CO_2 Storage

Monitoring

Accurate measurement of migrating CO_2 is necessary to verify models and to give early warnings of deviations, allowing timely intervention and remediation. Accurate and reliable monitoring techniques are crucial for safe storage and compliance with laws and regulations and help to increase public acceptance.

The SINTEF 3D Full Waveform Inversion (FWI) code was optimised for computational performance to allow finer grid models, enabling imaging of the thin CO_2 layers of the Sleipner plume. The handling of free-surface conditions was improved while a new elastic FWI code was implemented to take complex seismic wave-propagation effects into account.

A new uncertainty quantification technique was applied to both synthetic EM data and real seismic data from Sleipner. Simulations showed uncertainty is clearly reduced when inverting for the given data, while uncertainty was also reduced when using seismic data. The research team believes this is the first time that uncertainty has been calculated for CSEM/FWI CO_2 monitoring results.

An inverse method for estimating distribution of CO_2 in the reservoir at Sleipner as a function of time using a combination of travel-time anomaly and

amplitude measurements was developed, while pressure and saturation changes at Snøhvit (Tubåen) were successfully discriminated using two different techniques with seismic baseline and repeat data.

Containment
Researchers from SINTEF Petroleum Research, NTNU, GEUS (Denmark) and BGS (UK) collaborated to improve understanding of the fundamental effects of CO_2 injection on storage reservoir and caprock geomechanical properties, and to lower the uncertainty on the potential ill-effects such as leakage.

While SPR concentrated on investigating near-well risks related to thermal stress, fatigue due to cyclic injection operations, cement-to-rock bonding and fracture healing by creep of shale formations, BGS focused on fault reactivation experiments.

Accurate and reliable monitoring techniques are crucial for safe storage and compliance with laws and regulations and help to increase public acceptance.

Unique rock physics investigations at seismic frequency provided a translation map from laboratory ultrasonic velocities to seismic frequency, invaluable for more accurate monitoring in repeat geophysical surveys. BIGCCS was central in contributing to the development of simulation methods for field-scale explicit geomechanical analysis, resulting in SPR's fracturing code named MDEM. In 2016, a laboratory rig was built to study the effect on rock physics of partial CO_2 saturation, once again to help monitoring interpretation.

While it is too early to show specific adoption of results by partners, many have expressed the importance of including geomechanical research in common funding applications.

Enabling large scale CO_2 storage and EOR
Much research was conducted on case studies on CO_2 storage sites with high injection rates.

A thorough stability analysis of the convective mixing caused by density differences between CO_2-rich and CO_2-poor brine near the water-gas-boundary in a storage reservoir took place, leading to better estimates for when the onset of convection can be expected.

Large-scale injection of CO_2 into a storage site may soon be constrained by near-well pressure increase, i.e., the injection rate must be limited to avoid risk of fracturing of the formation and cap rock, and of reactivation of pre-existing faults and fractures.

To make reliable predictions of the safe pressure increase a robust geomechanical model is needed, including knowledge of rock strength, pore pressure, properties of existing faults and knowledge of the principal stress magnitudes and orientations in the area. BIGCCS tested and improved a methodology for the estimation of the stress field based on data from borehole breakouts, image logs and leak-off tests.

The pore pressure increase in the storage formation will also affect other potential storage sites that are in hydrodynamic communication. To make better use of resources, the efficiency of well placement choices and operation modes when extracting brine from the storage formation through one or more production wells was examined.

Several earlier studies have indicated that the use of captured CO_2 for large-scale development of CO_2-EOR in the North Sea can have a positive net present value for the transport and storage part of a CCS chain. The BIGCCS value chain model included updated CO_2-EOR modules and scenarios for development were presented at conferences.

AWARDS AND RECOGNITIONS

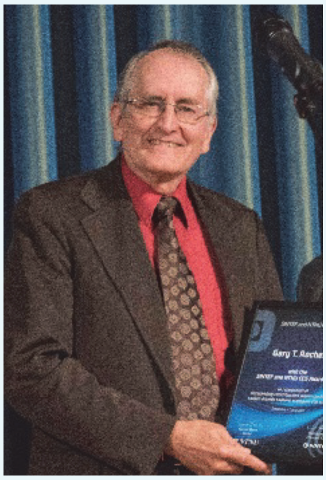
Both young and seasoned BIGCCS individuals have been recognized for their hard work and contributions on the international arena. That makes us proud!

- PhD student **Sissel Grude** won the ***EAGE Young Scientist Prize*** at the second Sustainable Earth Sciences conference in Pau (France) on October 3, 2013 for her presentation entitled *"Pressure Effects Caused by CO_2 Injection in the Snøhvit Field".*
- *Dr.* **Andrea Gruber**, together with Sankaran, Hawkes and Chen, was awarded a ***Focus on Fluids special feature*** by the Journal of Fluid Mechanics in September 2010, for the paper *"Turbulent Flame–Wall Interaction: a Direct Numerical Simulation Study".*
- PhD students **Christian Eichler** and **Georg Baumgartner,** and Prof. **Thomas Sattelmayer** received the ***ASME Gas Turbine Award*** and ***the ASME IGTI Combustion, Fuels and Emissions Best Technical Paper Award*** in 2011, for the paper *"Experimental Investigation of Turbulent Boundary Layer Flashback Limits for Premixed Hydrogen-Air Flames Confined in Ducts"* published by the ASME Journal of Engineering for Gas Turbines and Power.
- PhD student **Georg Baumgartner**, Boek and Sattelmayer received the ***ASME IGTI Combustion, Fuels and Emissions Best Technical Paper Award*** 2015 for the paper *"Experimental investigation of the transition mechanism from stable flame to flashback in a generic premixed combustion system with high-speed micro-particle image velocimetry and micro-PLIF combined with chemiluminescence imaging".* It was published by the ASME Journal of Engineering for Gas Turbines and Power.
- PhD student **Georg Baumgartner** received the ***Best Presentation Award*** for his presentation *"Study of Flame Flashback Phenomena for the Safety of Hydrogen-Rich Fuel Burners"* at the joint BIGCCS/CLIMIT PhD Seminar in Trondheim, Norway, on October 17-18, 2014.
- Dr. ***Mario Ditaranto was invited as keynote speaker*** on gas turbine combustion for CCS at the *XXII International Symposium on Combustion Processes,* Poland, 2015
- Dr. **Svend Tollak Munkejord** was invited to write a **review article** in Applied Energy. The article entitled *"Data and models – A review",* is found in Volume 169, May 1, 2016, Pages 499–523
- Dr. **Malin Torsæter** was ***invited speaker*** at the Tekna CO_2 conference both in 2014 and in 2016. She was also invited as ***keynote speaker*** at the American Geophysical Union (AGU) fall meeting in San Francisco in 2014. The BIGCCS-work relevant for well plugging was also presented in an invited presentation at the Offshore North Sea (ONS) conference in Stavanger in 2016.
- Dr. **Simon Roussanaly** received a ***best presentation award*** at the ICAEM 2016 conference in Kulua Lumpur, Malaysia. The presentation was titled *"Enabling CO_2 capture through integrated techno-economic assessments: The example of post-combustion membrane"*
- PhD student **Chao Fu** received the ***2012 Young Researcher Award*** from the Separations Division of the AIChE for his innovative ideas to reduce energy consumption in air separation processes for oxy-combustion as a scheme to carbon capture in coal based power plants.
- Prof. **Sally Benson** of Stanford University was given the ***2012 Greenman Award*** at the GHGT-11 conference in Kyoto, Japan. She received the award for her long-time efforts in studies related to geologic carbon dioxide sequestration in saline aquifers.
- Prof. **Hallvard Svendsen** received the ***2014 Greenman Award*** at the GHGT-12 conference in Austin Texas, USA. He was award for his dedication in development of the amine technology, and for his focus on education of PhD candidates.
- Dr. **Erik Lindeberg**, SINTEF, received the ***2011 SINTEF and NTNU Award*** at the TCCS-6 conference for his pioneering efforts in storing CO_2 in geological strata and for producing the basic concept of storing CO_2. This was the first time the price was presented.

- Dr. **Tore A. Torp**, retired from Statoil, was given the ***2013 SINTEF and NTNU Award*** at the TCCS-7 conference for his efforts and pioneering role within geological CO_2 storage and for his contributions to knowledge dissemination.

- Prof. **Gary T. Rochelle**, University of Texas at Austin, received the ***2015 SINTEF and NTNU Award*** at the TCCS-8 conference for his long-lasting contributions within CO_2 capture, and in particular for his efforts in development of post-combustion technologies.

The Greenman Award is presented by the GHGT Conference series as a means to recognize individuals who has made a significant contribution to the field of CO_2 removal, storage and utilization.
The award was given to **Sally Benson** (BIGCCS Scientific Committee member) in 2012, and to **Hallvard Svendsen** (BIGCCS Board member) in 2014.



The SINTEF and NTNU CCS Award is presented by SINTEF and NTNU at the Trondheim CCS Conference series every second year. The award is given to an individual for outstanding achievements within the field of carbon capture, transport and storage (CCS). Three central BIGCCS individuals have receive the price: **Erik Lindeberg**, SINTEF Petroleum (2011), **Tore A. Torp**, Statoil (2013), and **Gary T. Rochelle** (Scientific Committee member), University of Austin at Texas (2015).

INNOVATIONS BIGCCS

Innovation was a central element in BIGCCS activities, and throughout the project a total of 46 innovations were registered and documented (responsible task below the innovation).

CO_2 Capture

- *Precipitating CO_2 absorbent*
  Solvent technology
- *Tubular oxy-fuel membrane combustor*
  Innovative membrane technologies
- *A novel distributed injection system for hydrogen-rich gaseous fuels*
  Enabling H_2 fueled turbines
- *An analytic model for prediction of flashback in turbulent confined flows*
  Enabling H_2 fueled turbines
- *Low emission low penalty pre-combustion capture with exhaust gas recirculation concept*
  Oxy-fuel technologies
- *Burner for oxy-fuel gas turbine*
  Oxy-fuel technologies
- *Oxy-fuel high pressure combustion rig*
  Oxy-fuel technologies
- *EGR burner*
  Oxy-fuel technologies
- *Low temperature process for CO_2 capture by liquefaction*
  Application to industry and offshore
- *An excel-based tool for calculating heat and mass balances for the CLC process*
  Application to industry and offshore
- *A self-sustained process for hydrogen production with CO_2 capture from gasified coal, combining the advantages of palladium membranes and low-temperature CO_2 capture*
  Application to industry and offshore

- *Attainable region approach for design of membrane processes for end-of-pipe capture*
  Application to industry and offshore, and CO_2 value chain
- *Oxy-FCC reactor model for designing and optimizing oxy-FCC process for CO_2 capture in refinery*
  Application to industry and offshore
- *Burner of H_2 combustion with applications in the refinery industry*
  Application to industry and offshore
- *Post combustion capture from the natural gas combined cycle (NGCC) with calcium looping (CaL)*
  Integrated assessment
- *Novel benchmarking methodology for comparing different CO_2 capture technologies: evaluating the difference between the thermodynamic maximum efficiency and the technology-limited efficiency*
  Integrated assessment
- *The 3 kW CLC test rig*
  Looping technologies
- *Powder production*
  Looping technologies
- *The 150 kW CLC test rig*
  Looping technologies

CO_2 Transport

- *Numerical tool for fracture propagation control issues in pipelines*
  CO_2 pipeline integrity
- *Redesign for CCS fluids and conditions of setup for measurement of density and speed of sound*
  CO_2Mix
- *Gravitational preparation of calibration gas*
  CO_2Mix
- *CO_2Mix phase equilibria setup*
  CO_2Mix

CO_2 Storage

- *Methodology for CO_2 quantification based on Controlled Source ElectroMagnetics (CSEM) and Full Waveform Inversion (FWI)*
  Monitoring
- *CO_2 pressure and saturation discrimination using time-lapse seismic data*
  Monitoring
- *High-resolution CO_2 monitoring using acoustic and elastic full waveform inversion*
  Monitoring
- *An automated CO_2 leakage detection tool*
  Monitoring
- *Quantification of uncertainty in geophysical monitoring methods*
  Monitoring
- *Stability analysis for diffusion-driven convection*
  Reservoir containment
- *Method for assessing thermal tensile strength of caprock*
  Reservoir containment
- *Method for assessing thermal tensile strength of caprock*
  Reservoir containment
- *Method for assessing the mechanical properties of the cement to rock interface*
  Reservoir containment
- *Fluid saturation dependent seismic dispersion in shale*
  Reservoir containment
- *Sealing efficiency of caprock shales*
  Reservoir containment
- *Fault reactivation bespoke shear rig*
  Reservoir containment
- *Method for determining permeability of defects in/along well cement*
  Well integrity
- *Model for sealant placement in wells*
  Well integrity
- *Use of CO_2 for closing cracks in well cement*
  Well integrity
- *Method for determining safe temperature intervals* for CO_2 wells
  Well integrity
- *In-situ X-ray tomography studies of cements for safe plugging of CO_2 wells*
  Well integrity
- *Manipulating cement-steel bonding in CO_2 wells*
  Well integrity
- *Operating pressure management in large-scale CO_2 storage*
  Enabling large-scale CO_2 storage and EOR
- *Analysis of safe injection pressures*
  Enabling large-scale CO_2 storage and EOR
- *Implementation of water production on Bunter*
  Enabling large-scale CO_2 storage and EOR

CO_2 Value Chain

- *The iCCS tool*
  CO_2 Chain analysis
- *Method to guide polymeric membrane material development based on integrated techno-economic assessment*
  CO_2 Chain analysis

INTERNATIONAL COOPERATION

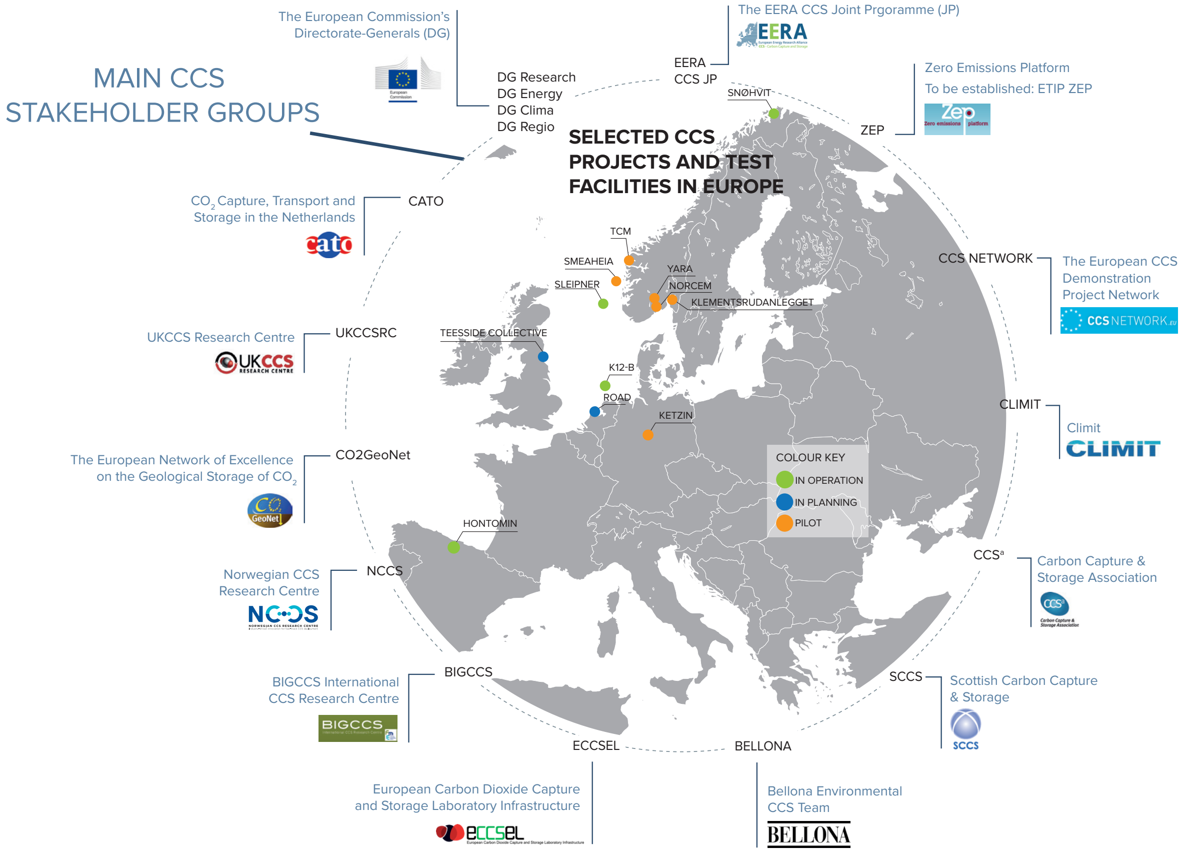
CO_2 knows no boundaries. Neither does knowledge.
So, there was no reason why BIGCCS shouldn't go fully international.

Setting the CCS agenda

As one of the largest CCS research centres worldwide, BIGCCS took an active role in the development of European CCS strategy both at the research and academic levels.

The *CCS Joint Programme* (CCS-JP) under the European Energy Research Alliance (EERA JP-CCS) is an authority on CCS research, development and innovation. The CCS-JP provides strategic leadership to its excellent, but dispersed, energy research partners. Furthermore, it coordinates both national and European R&I programmes to maximise synergies, facilitate knowledge sharing and deliver economies of scale to accelerate the development of CCS. The CCS-JP was launched at the SET-Plan Conference in Brussels in November 2010. From 2013 to 2015, Dr. Nils A. Røkke was coordinator of the CCS JP, while Dr. Marie Bysveen was vice coordinator, and from 2015, Dr. Bysveen held the coordinator role. The CCS JP has contributed extensively to the SET Plan Integrated Roadmap.

Carbon Capture, Transport and Storage (CCS) in Europe



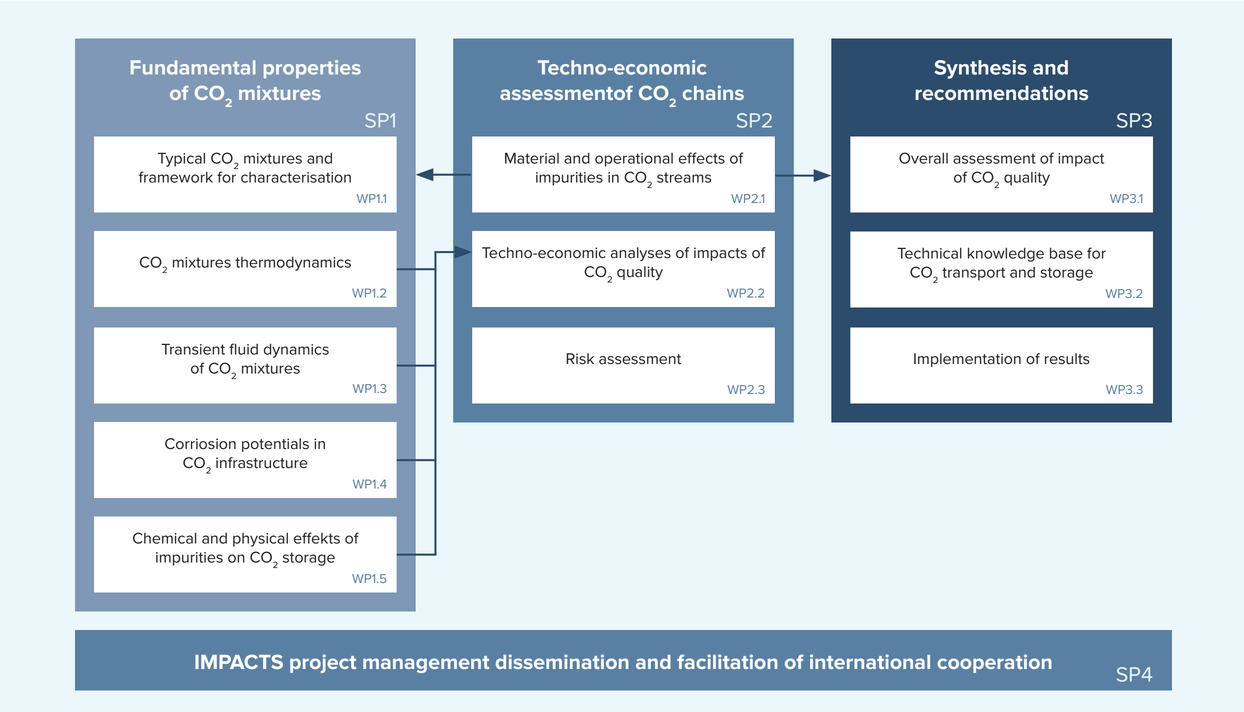
Dr. Nils A Røkke has since 2010 been co-chair of *the European Technology Platform for Zero Emission Fossil Fuel Power Plants* (***ZEP***). Founded in 2005, ZEP is a coalition of stakeholders united in their support for CO_2 capture and storage as a key technology for combating climate change. ZEP serves as advisor to the European Commission on the research, demonstration and deployment of CCS.

ZEP was born out of the EU's recognition of CCS as a key component of any future sustainable energy system. Its mission is to identify and remove the barriers to creating highly efficient power plants with near-zero emissions.

EU projects

Under the Horizon 2020 programme, SINTEF via BIGCCS coordinates two projects, Gateway and CEMCAP. The ***GATEWAY*** project will provide a common strategic decision basis, enabling stakeholders to identify and implement measures that can accelerate development and deployment of technologies needed for realisation of large-scale CCS projects based on European CO_2 transport infrastructure. The two-year project started in May 2015, has six partners, and a budget of €787,000. Dr. Marie Bysveen (SINTEF) is the project manager.

The ***CEMCAP*** objective is to pave the ground for large-scale implementation of CO_2 capture in European cement industry. CEMCAP demonstrates CO_2 capture technologies in environments relevant to industry, such as existing pilot-scale test rigs adapted to replicate realistic cement plant operating conditions along with a dedicated clinker cooler for oxyfuel cement plants. Cost and energy efficient retrofit of the capture technologies are targeted with a focus on product quality. With a duration of 42 months and 15 partners, the project began in May 2015 with a budget



of €10 million. Dr. Kristin Jordal (SINTEF) is the project manager.

IMPACTS is a collaborative project co-funded by the European Commission under the 7th Framework Programme. The goal of IMPACTS is to close knowledge gaps related to transport and storage of CO_2-rich mixtures from various CO_2 sources to enable realisation of safer and cost-efficient solutions for CCS. IMPACTS addresses the impact of impurities in captured CO_2 from power plants and other CO_2-intensive industries on CO_2 transport and storage. This encompasses fluid properties, phase behaviour and chemical reactions in the infrastructure complex and at the storage sites. Results from IMPACTS will help to ensure safe and reliable design, construction and operation of CO_2 pipelines and injection equipment, and safe long-term geological storage of CO_2. The project began in 2013 with 17 partners and has a budget of €5.6 million. Dr. Sigmund Størset (SINTEF) is the project manager.

Exchange of research personnel

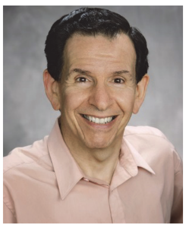
In terms of combustion technology, the BIGCCS Centre has been fortunate to cooperate with Dr. Alan Kerstein of Sandia National Laboratory. As one of the world's leading experts with an exceptional standing in his field, Dr. Kerstein visited BIGCCS in Trondheim several times during the last years of the Centre, often staying for weeks at a time. The Centre benefitted from his strategic capabilities as well as his enthusiasm in solving concrete challenges. Dr. Kerstein opened doors to cooperation with the best US combustion research groups and has also served as a member of the BIGCCS Scientific Committee.

Sigurd Sannan and ***Andrea Gruber*** both visited University of Berkley and the Combustion Research Facility at Sandia National Laboratory several times. The joint work focussed on numerical simulations in combustion processes. Particularly useful was the powerful computational power of the mainframes at these two sites. Sandia National Laboratories contributed an estimated 100 million CPU-hours. This has enabled accurate calculations of flame behaviour in combustion machinery.

Simon Roussanaly visited Carnegie Mellon University in Pittsburgh (PA, USA) for seven weeks

Sigurd Sannan

Andrea Gruber



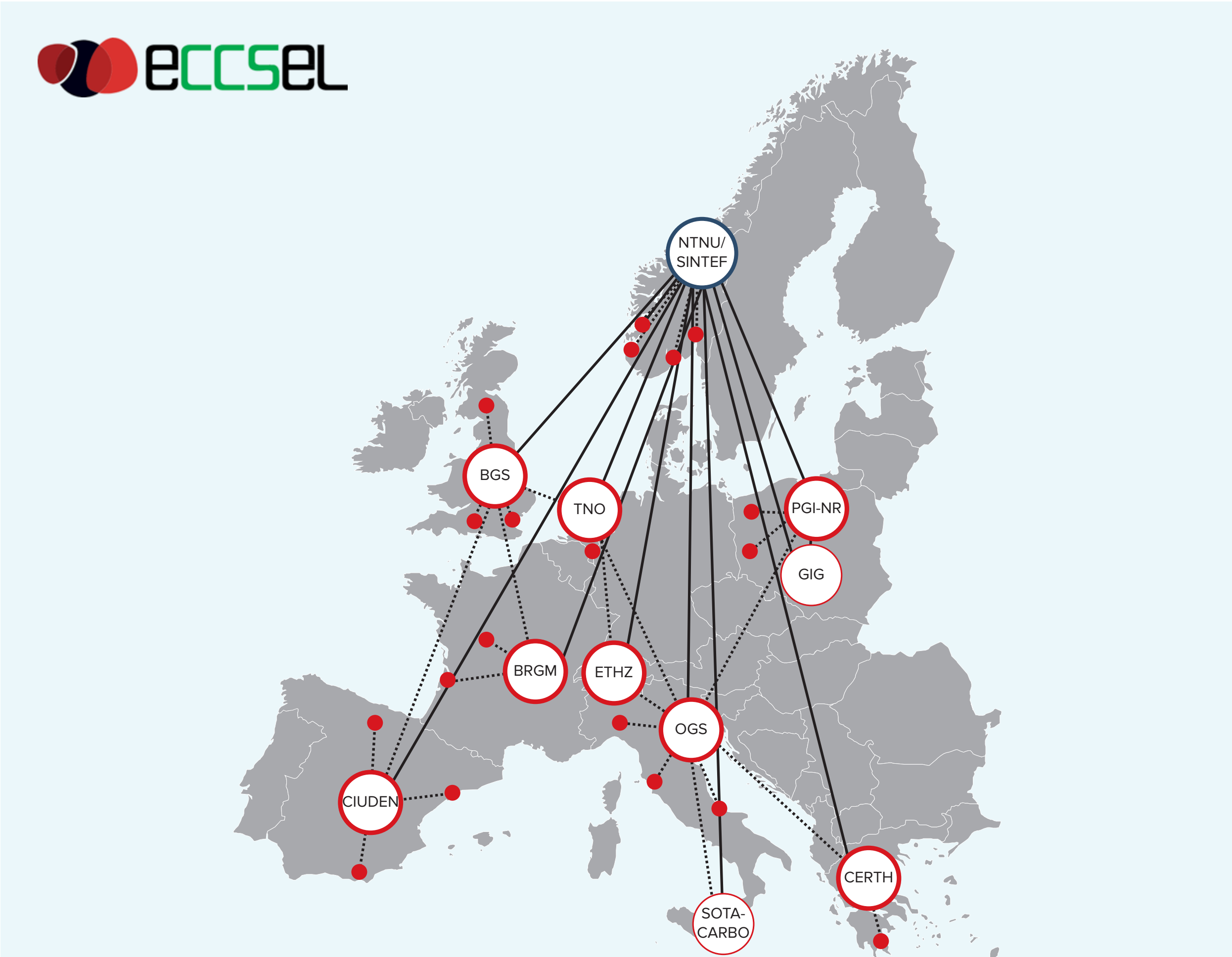
Alan Kerstein

Professor Haibo Zhai and Simon Roussanaly on the Carnegie Mellon University campus, September, 2015.

in 2015. Together with professors Haibo Zhai and Edward Rubin at the Engineering and Public Policy Department, he studied the enabling of CO_2 capture from coal power plant using membranes. The collaboration led to identification of competitive membrane properties for the membrane-based processes relative to MEA-based CO_2 capture in a post-combustion coal-fired power plant.

Preparing for increased exchange of researchers and students

BIGCCS cooperated with the Norwegian node of *European Carbon Dioxide Capture and Storage Laboratory Infrastructure* (ECCSEL). Proposed by SINTEF and NTNU on behalf of the Norwegian Government, ECCSEL was put on the official European Strategy Forum on Research Infrastructures (ESFRI) updated Roadmap in 2008. The objective is to open access for researchers to a top quality European research infrastructure devoted to CCS technologies.



The ECCSEL network.

The ECCSEL consortium teams up selected Centres of excellence on carbon capture and storage research (CCS) from nine countries across Europe. The mission is to implement and operate a European distributed, integrated research infrastructure initially based on a selection of the best research facilities in Europe.

Bringing the CCS world together

During its course, BIGCCS organised the bi-annual Trondheim Conference on CCS (TCCS) three times, in 2011, 2013, and 2015. TCCS is established as a leading scientific conference that brings together 350-450 participants from all around the world. ***TCCS-9*** is scheduled for June 12-14, 2017. Nils A. Røkke is the Chair of the conference.

The *SINTEF and NTNU CCS Award* was established in 2011 as a means to increasing the attention about the TCCS conference. The award is presented at the TCCS conference when worthy candidates are identified.

Opening session at TCCS-7, 2013.

The three winners so far are Erik Lindeberg, SINTEF (2011), Tore A. Torp, Statoil (2013), and Gary T. Rochelle University of Texas at Austin (2015).

Key research groups and partners

BIGCCS benefitted from cooperation with the following research groups:

- The Combustion Analysis Lab at University of Berkeley (California, USA) and Professor Robert Dibble. University of Berkeley is one of the world's leading research groups on combustion.
- The Combustion Research Facility at Sandia National Laboratory, USA, which is the U.S. Department of Energy's premier site for research in combustion technology.
- Ruhr Universität Bochum and Professor Roland Span. This research group is among the highest ranking in the field of characterisation of thermophysical properties of fluids, including CO_2 and CO_2 mixtures.
- Nordic CCS Research Centre (NORDICCS). This is primarily a networking collaboration between R&D institutes and the industry in the Nordic countries with a focus on CCS deployment.
- European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL). The ECCSEL mission is to develop a Europe-wide distributed, integrated research infrastructure, involving the construction and updating of research facilities.

In addition, BIGCCS personnel have actively participated in activities spearheaded by a number of other international organisations outside of the Centre (see separate text box below):

Cooperating entities

Air Liquide (France), Brigham Young Univ. (USA), Carnegie Mellon Univ. (USA), Colorado School of Mines (USA), CORIA-Univ. de Rouen (France), Corning S.A. (France), Czech Academy of Science (Czech Republic), European Energy Research Alliance (EERA), Freie Universität Berlin (Germany), Georgia Tech Univ. (USA), Global CCS Institute (Australia), IFP (France), International Energy Agency (IEA), Lawrence Livermore National Laboratory (USA), Lund Univ. (Sweden), Massachusetts Institute of Technology (USA), Mälardalen Univ. (Sweden), National Energy Technology Laboratory (USA), National Institute of Advanced Industrial Science and Technology (Japan), National Institute of Standards and Technology (USA), National Renewable Energy Lab (USA), North Carolina State Univ. (USA), Resources for the Future (USA), RWTH Aachen Univ. (Germany), Saint Gobain (France), Princeton Univ. (USA), Stanford Univ. (USA), TNO (Netherlands), Univ. du Maine (France), Univ. of North Dakota (USA), Univ. of Regensburg (Germany), Univ. of Western Australia (Australia).

TRAINING OF RESEARCHERS

A very large education programme for PhDs, Postdocs and Master students was central to the BIGCCS Centre.

In total, 26 PhD candidates were recruited, 21 of whom defended their thesis, and 5 remained active at the end of the Centre. 8 Postdocs were recruited, of which 7 completed and one is due to finish in 2017. Finally, 52 Master students were registered with BIGCCS-related topics, and often worked closely with PhD students in BIGCCS.

A total of 110 journal papers were published with one or more PhD/Postdocs as main author or co-author. The education program in BIGCCS had a very high quality and an extremely high efficiency. Only one PhD candidate dropped out after 6 months, and 5 PhDs needed extra funding from BIGCCS for a combined total of 10 months.

The international nature of BIGCCS was reflected in the education program. A total of 12 countries were represented in the group of PhDs and Postdocs, with the largest contingencies from Iran (7), Norway (6), Germany (5) and China (4). BIGCCS attracted 11 talented young researchers into Norway: Five from Iran, three from China, and one each from Poland, Bangladesh and France. These numbers will increase when the remaining researchers complete their work for BIGCCS. Only three of those who studied in Norway returned to their home country. The gender distribution was 24% female and 76% male.

Prof. Truls Gundersen, leader of the academic program.

A total of 21 professors were active in the supervision of PhDs and Postdocs. 16 of these were at NTNU (supervising a total of 26 candidates), two were at the University of California, Berkeley (supervising two candidates), and one each at the Technical University of Munich (supervising three candidates), the University of Oslo (supervising two candidates) and Ruhr University of Bochum (supervising one candidate).

The PhDs and Postdocs were involved in research areas covering the entire scope of BIGCCS. In Capture (SP1), topics such as membranes, combustion (hydrogen, oxy-fuel and chemical looping), industrial applications and integrated assessments were studied by 16 PhDs and two Postdocs. In Transport (SP2), topics such as pipeline integrity and physical properties for CO_2 mixtures were studied by three PhDs and one Postdoc. In Storage (SP3), topics such as Q&M for storage, storage behaviour, monitoring, leakage and effects of CO_2 on rock properties were studied by seven PhDs and four Postdocs. Finally, in CO_2 Value Chain (SP4), research in chain analysis was conducted by one Postdoc.

Christian Eichler and Georg Baumgartner, supervised by Thomas Sattelmayer at the Technical University of Munich, received the ASME Gas Turbine Award for their research in hydrogen combustion at the Turbo-Expo in San Antonio, USA, in June 2013.

Sissel Grude, supervised by Martin Landrø in the department of Petroleum Technology and Applied Geophysics at NTNU, received the EAGE (European Association of Geoscientists and Engineers) award for young researchers for innovative contributions to sustainability and geological resources. The award was given at a conference in Pau, France, in September 2013.

Chao Fu, supervised by Truls Gundersen in the department of Energy and Process Engineering at NTNU, received the Young Researcher Award from the Separations Division of the AIChE for his innovative ideas to reduce energy consumption in air separation processes for oxy-combustion as a scheme to carbon capture in coal based power plants. The award was given at the AIChE Annual Meeting in Pittsburgh, USA, in November 2012.

To help develop a family feeling for the PhDs and Post-docs working across such a diversity of areas, internal seminars with presentations and social dinners were arranged in the early days of BIGCCS. Later, CLIMIT held PhD Seminars on an annual basis, every other year organised as part of the BIGCCS Consortium Days. The CLIMIT Seminars gave PhDs and Postdocs the opportunity to make presentations to a broader audience, including the user partners of BIGCCS.

Participants at the 2015 PhD seminar in Trondheim visiting the SINTEF CO_2 laboratory.

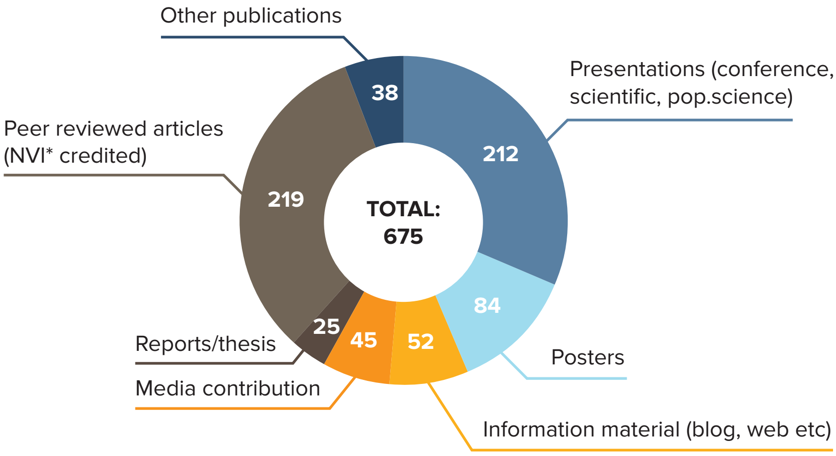
In reflecting over her PhD project, Vera Hoferichter of TUM says:
- For young researchers at TUM, BIGCCS offered perfect research opportunities. Frequent networking events and PhD seminars facilitated contact with other PhD students as well as experienced researchers from various fields. BIGCCS's high degree of multidisciplinary work was essential to keep in mind the greater goal of CCS research and permitted highly interesting insights into its various aspects. Being able to present your own work to an interdisciplinary audience was a great help in learning to extract key findings and their comprehensible communication. BIGCCS has created an excellent environment for CCS research and we are proud to be part of it.

Employment of PhD candidates

By Centre company	By other companies	By public organizations	By university	By research institute	Outside Norway	Other	Total
3	2	0	5	2	8	6	26

COMMUNICATION AND INFORMATION DISSEMINATION

It is said that research is of little value unless results are converted into practical use. “Practical use” of research does not happen unless the technology is known and generally accepted. Communicating results is therefore essential.



BIGCCS publications by type (2009–2017) (source: the Christin database, www.cristin.no)

BIGCCS has sought to be a source for objective information on research, development, status and potential of CCS for the research community, decision makers, technology providers, and society. Gaining coverage in publications other than scientific reports was a specific aim of the Centre, to ensure a higher degree of visibility, citations, and contributions to future funding for the research institutes. Communication with non-experts was also an important aim.

Proof of the pudding

The ultimate proof of high quality research is through the acceptance of articles in high-ranking scientific journals. 176 scientific articles relevant to BIGCCS research were published in some of the research world's most prestigious journals.

Må gjøre gassen klimanøytral

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

Kick-off for månelanding

Stor dag for klimateknologene ved Sintef og NTNU i Trondheim i går. Ekspertene på CO_2-håndtering hadde sin første samling.

Klimaløsning i rør

Debatt

Norge bør lagre CO_2 for Europa

Gathering the CCS world in Trondheim

The Trondheim CCS Conference (TCCS) began in 2003 as a purely scientific conference. After a modest start, the conference is now established as one of the most significant CCS conferences. Under the auspices of SINTEF and NTNU, BIGCCS was responsible for organising three conferences in 2011, 2013, and 2015. During the BIGCCS period, each conference had 350-450 participants, 150 oral presentations, and around 100 posters. Both oral and poster presenters were given the possibility to publish scientific papers in a journal after the conference. The conferences generated much beneficial publicity for BIGCCS.

Nils A. Røkke opens TCCS-8 on June 17, 2015

Communicating with the masses

Norwegian newspapers

BIGCCS produced a series of feature articles in the Norwegian newspapers Dagens Næringsliv, Aftenposten, Stavanger Aftenblad, and Adresseavisen. In the examples below Dr. Nils A. Røkke argues that the Government's CCS strategy should have focussed on making the Norwegian export of natural gas climate neutral, while Dr. Svend Tollak Munkejord, Dr. Mona Mølnvik and Dr. Cato Dørum advocate safe pipeline transport of CO_2. Dr. Erik Lindeberg and Dr. Grethe Tangen suggest that Norway could host a central CO_2 storage site accommodating storage volumes for the whole of Europe.

National Television – TV2 Nyhetskanalen

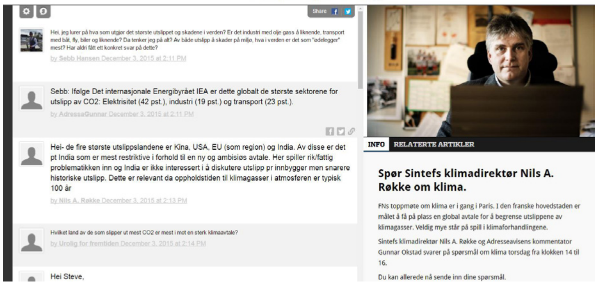
After the successful COP21 meeting in Paris in December 2015, Dr. Nils A. Røkke appeared live on TV2 Nyhetskanalen. He was interviewed about

the agreement coming out of the meeting and the implications to Norway and future policymaking.

Web meeting at Adresseavisen

In connection with the COP21 meeting in Paris in December 2015, Dr. Nils A. Røkke participated in a web meeting with readers of Adresseavisen. The title of the meeting was "Ask about the climate", and Dr. Røkke answered questions posted by the readers of the newspaper.

Nettmøte - spør om klima



Daily communication – Web and Blog

The Centre website (www.bigccs.no) was an important tool for communication. The website was redesigned in 2014 with a better format to improve readability, especially on mobile devices. The website received around 1,000-1,200 views per month.

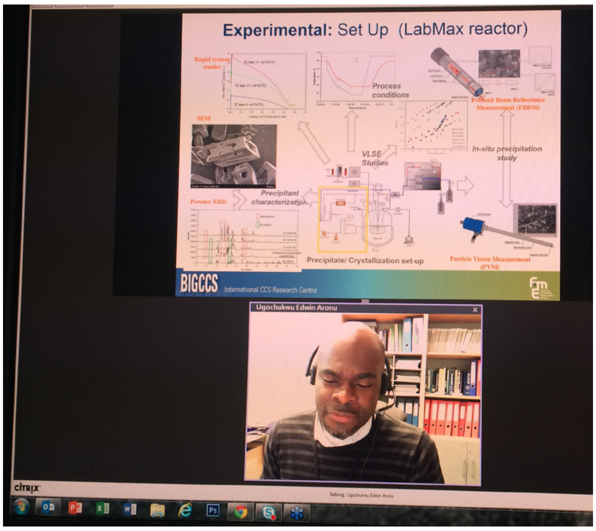
A new feature on the redesigned website was the blog, where researchers presented their work in a simplified language aimed at non-experts. In the blog below, Dr. Sigurd Løvseth writes about new and highly accurate CO_2 mixture property knowledge needed for efficient and robust CCS. More than 50 blog posts were produced during the last two years of the Centre.

Newsletter

Each year the Centre produced 6-8 newsletters, which gave short introductions to research results, ongoing activities, and events. Around 400 people received the newsletter.

Webinars

Webinars proved to be a particularly useful tool to communicate with the user partners, as it created an opportunity for more individuals to participate without costly traveling. During the spring of 2016, BIGCCS offered a series of 14 webinars, which were open to individuals from all BIGCCS partners.



Ugochukwu Edwin Aronu giving a webinar.

The Prime Minister opened the BIGCCS Centre

When BIGCCS held its kick-off meeting on June 22, 2009, then Prime Minister Jens Stoltenberg officially opened the Centre via video. He underlined that CCS is a key technology that will enable us to provide the world with the energy it needs, while at the same time reducing CO_2 emissions. The video along with a few other films can be watched on ***YouTube***.

Prime Minister Jens Stoltenberg.

EFFECTS OF THE CENTRE FOR THE OVER-ARCHING GOAL OF THE FME PROGRAMME

The Centre has worked steadily towards it's targets and the overarching objectives of the Norwegian Parliaments climate agreement in 2008 by:

Providing new tools and models for assessing CO_2 storage capacity and qualification in close co-operation with the industry. This will enable more widespread carbon dioxide storage at the Norwegian Continental shelf. This is a key element in decarbonising the industrial sector in Norway to start a transport and storage business by also allowing for foreign CO_2 being received. This will be key in addressing emission reductions for the petroleum sector and the industry. These are major emission contributors in the Norwegian climate budget.

Creating a basis for innovations and important spin-out projects that are contributing to lower cost and new value chains for petroleum in a low emission society. Examples of such spin-off projects are new solvent systems and processes and membrane separation of hydrogen. The latter is an element in new business models for natural gas- to sell decarbonised fuels on the global market. New burner concepts have also been conceived to enable combustion of hydrogen rich fuels in gas-turbines with controlled nitrous oxide emissions and high efficiency. These are key enabling technologies for achieving reduced GHG emissions in Norway and on a global scale. It may also be applicable for offshore installations, which else are hard to curb emissions from.

Pioneering new knowledge and processes for transport of CO_2 by ships and pipelines by optimising the process in the interfaces of capture, transport and storage. By finding matching conditions along the value chain and make use of these to optimise the solution with regards to cost, efficiency, footprint and operability.

Initiating and promoting international co-operation to secure uptake of the results and to make benefit of new impulses at a global scale. This also includes the establishment of research infrastructure at European scale through ESFRI[1]. This will enable fast tracking CCS as research infrastructures are key for technological development and understanding.

[1] European Strategy Forum for Research Infrastructures- in this context ECCSEL – European CCS Labs- a landmark project of ESFRI hosted by Norway through NTNU in close collaboration with SINTEF.

EFFECTS FOR THE HOST INSTITUTION AND THE RESEARCH PARTNERS

SINTEF's CCS research strategy from the early 2000s had an ambitious targets to set up a completely new research field. Mission accomplished!

CCS on the research agenda

During the 1980s and 1990s, it became increasingly evident that the rising CO_2 levels in the atmosphere could pose a serious threat to the global environment. On this basis, SINTEF included CCS in the strategic research plan around the turn of the century. This was a logical consequence of SINTEF's vision: "Technology for a better society".

The plans for the BIGCCS Centre represented a significant ramp-up in SINTEF's activity level in CCS. With the goal of enabling full-scale CCS implementation, it was clear that more people, more projects and more infrastructure was needed. The mission was to develop the necessary knowledge base and new technologies throughout the CO_2 chain, for capture, transport, and storage.

Beyond expectations

The BIGCCS Centre has made it possible for SINTEF to not only fulfil, but also over-achieve on its goals for the CCS research strategy developed in the early 2000s:

- Highly competent *research groups* have been established within the fields of CO_2 capture, transport, storage, and value chains. Whereas ten years ago specific research areas were non-existent or staffed with just a few researchers, most of the crucial areas have functioning groups today.
- A new generation of capable *CCS researchers*, both at the doctorate and the master level, has been educated to ensure excellent recruitment opportunities for research groups at SINTEF and NTNU. As intended, candidates are also finding employment with the BIGCCS industrial partners.
- The possibility to "prove theories in practice" is crucial on the way towards full-scale CCS implementation. For this purpose, advanced *research infrastructure* has been added to laboratories, and laboratories have been upgraded. Relevant infrastructure plays an important role in innovation activities.
- Together, SINTEF and NTNU have spearheaded the Norwegian node of *ECCSEL*. This activity is expected to foster increased researcher exchange, future cooperation, and more efficient exploitation of European research infrastructure.
- SINTEF's current portfolio of *CCS projects* is significant. National and EU projects have been added to the portfolio in numbers larger than hoped ten years ago. Some of these projects have been an integral part of BIGCCS, while others are operated independently.
- Strong and enduring *networks* have been built between industry and research partners. These networks will play a crucial role in the next phase of CCS deployment.

The research partners have, in general, expressed great satisfaction with BIGCCS. Especially, this is true when it comes to the duration of the project, and the fact that BIGCCS covered the whole value chain.

In the 2012 BIGCCS annual report, Professor May-Britt Hägg, NTNU, said this about BIGCCS: "A lot of good work has already been done, and I am particularly keen on the academic programme, with its PhD training and the publication scheme", and "Even though the EU does a lot of research on CCS, BIGCCS is different. The programme is a good opportunity to look at the whole value chain. I am sure that many scientists all over Europe would like to join if they had the chance.

Professor Truls Gundersen, NTNU, adds that "BIGCCS has been an important funding source for PhD students and Post.docs, and the Centre has given the candidates access to a large network of researchers and industrial representatives. BIGCCS has also given NTNU an opportunity to collaborate across faculties and departments".

Ready to face the future

SINTEF's CCS research strategy has been revised based on the experiences from BIGCCS. The Norwegian CCS Research Centre (NCCS) is the new cornerstone to realize this strategy. Central elements are deployment and innovation.

BIGCCS has made possible the establishment of a new and competitive research field in Norway. The Norwegian CCS research community now possesses the people, infrastructure, and knowledge crucial in continuing its CCS leadership. We are proud and prepared to face the challenges of the deployment phase.

What research partners say about BIGCCS ...

Andy Chadwick, BGS (UK)

- The benefits to BGS of partnering in the BIGCCS FME have been very significant. Our involvement in the Centre has enabled us to maintain close collaborative contact with leading CCS researchers in Norway and Denmark, and to share experience and knowledge with technical and scientific specialists at SINTEF, NTNU and GEUS. We have also, through BIGCCS, maintained contact with key industry players such as Statoil with whom we have had a good relationship in terms of research discussions, project development and access to the key monitoring datasets. This has been of huge benefit in furthering our research into understanding fundamental CO_2 *storage processes and the collaborations developed in BIGCCS have resulted in a number of high profile joint papers with both industry and academic partners. The wider context and influence of BIGCCS have also been of great help in retaining a wider European network of partners (particularly following the Brexit vote) and developing new research initiatives with the BIGCCS partners and other European organisations. So, for BGS, partnership in BIBCCS has been an unqualified success.*

Peter Kutne, DLR (Germany)

- The wide range of international and interdisciplinary research partners contributing to BIGCCS have fostered fruitful discussions and created new ideas (such as distributed hydrogen injection), which will be pursued. The open exchange of experiences and knowledge promoted our daily experimental research as well as opened up new perspectives for possible technical applications of results from the more fundamental research topics. The participation of industrial partners was very important because it helped to highlight technical relevant solutions and to evaluate the feasibility from an economic point of view.

Peter Frykman, GEUS (Denmark)

- GEUS gained extraordinary benefits from participation in BIGCCS activities. Right from the beginning, the project meetings gave rise to new ideas that were to be challenged by laboratory experiments or other methods. These discussions led to activities that we never otherwise would have had the resources to perform, and which in many cases led to conclusions we had not anticipated. The flexibility in the work programme also allowed us to stop activities at early stages based on lack of interesting results, and then quickly reallocate resources to other more interesting problems. The very broad range of expertise in the whole project group and the spirit of cooperation also resulted in co-authorships of a number of publications, which are now widely cited in the CCS community. The BIGCCS participation has contributed significantly to GEUS's technical and scientific profile in the field of geological storage.

EFFECTS OF THE CENTRE FOR THE COMPANY PARTNERS

The close working relationship between industry partners and researchers was key to the number of successful innovations.

BY DAVID NIKEL

Bringing several multinational corporations into an academic research group was not without its challenges, but the overall feedback from both sides has been positive.

“The past 8 years have been a journey we have taken together with industry,” says Centre Director Mona J. Mølnvik. “In the latter years of the Centre, many of our industrial partners told us they are much better positioned to do feasibility studies of full-scale projects due to the efforts of the Centre.”

“Being able to do strategic research over the long-term brought real focus onto specific CCS challenges. This enabled us to develop a deep knowledge base and innovation platforms, which helped to attract vendors for other related activities.”

Shell

Cato Christensen from Shell was involved in creating some of the early links between his firm and the research centre. He says there are many reasons why a major energy company would want to be involved in such research, despite the obvious risks to competition.

“Joining a research centre is attractive to us when we seek general progress in a field rather than working to build up our own intellectual properties. This is very much the case for CCS as the technology is not easy to progress on your own. We need industry, academia, research institutes and governments to pull this together. Also, it goes without saying that we look for the quality of the centre before we get involved.”

Getting involved in such a centre poses an interesting conundrum for industrial partners. The world of academia is built around the open sharing of information, something that doesn’t always fit with corporate strategy. Cato says it’s about striking the right balance.

“We of course have IP in many areas, including areas where we also might get involved in such open research. In such cases, we must decide whether it is the best strategy to keep our own IP separated from the open research or if we believe we will gain more by revealing our own IP to progress the research, even if this means disclosing it to the other industrial partners.”

In the BIGCCS 2014 annual report, Dr. Per Ivar Karstad, Statoil ASA, said this: "The energy industry needs to develop low carbon solutions as a response to the climate challenges. Statoil will be part of the solutions to this challenge. Fossil energy resources will be the dominant energy source in the future energy mix for many decades to come. CCS is the only technical solution to significantly reduce CO_2 emissions from these energy sources. CCS and BIGCCS is important to Statoil in being part of the solution to the climate change".

The work goes on

Centre Director Mona J. Mølnvik believes it was worth all the hard work to overcome the initial challenges: “It takes time to develop such strong personal relationships as the dynamic within industry is different from the research community. It’s not possible to bring together a complex consortium and expect effective working relationships from day one. We needed to learn to adapt to remain relevant over a longer period.”

"Many of the industrial experts are located overseas, so over time we discovered the most effective way to communicate was to build strong relationships to the Norwegian branches of the companies, then use webinars to make the results easier to access for the rest of the company."

"We can be proud of what we achieved within the time-frame of BIGCCS, but I know there will be many more benefits to come thanks to these relationships made within the work of the centre."

In a similar vein, these successful industry partnerships have paved the way for the creation of the Norwegian CCS Research Centre (NCCS), designed to help Norway meet its obligations under the Paris Climate Agreement. "Our participation in and experience from BIGCCS was an important basis for us supporting and joining NCCS," says Gassco's Gudmundur Kristjansson.

View from the partners

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

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

"Our participation in BIGCCS has supported Gassco personnel with CO_2 knowledge when leading and participating in technical CO_2 studies. Gassco considers the centre model to be an efficient way of doing research on broad topics like CCS, where all major stakeholders are represented. Although our particular interest was in CO_2 transport, we supported BIGCCS as a full-chain project to get confidence that important interfaces and boundaries for CO_2 capture and storage are sufficiently developed."

- Gudmundur Kristjansson, Manager R&D, Gassco

BIGCCS was a privileged place where we have been able to tackle both short-mid term operational issues and long-term knowledge building concerns. BIGCCS is also exemplary in the way the project has smoothly managed and encouraged positive collaborative interaction between academic, industry and state representatives working together on a common target. The most beneficial aspect for us was the access to a professional network of international talented experts along the whole CCS chain and we saw how technology improvements and breakthroughs can be decisive triggers in the context of a voluntary leading country in this domain.

- Remi Dreux, R&D Coordinator, Engie.

"Too often the focus of industry is on immediate results. The long-term focus of BIGCCS combined with a consistent flow of innovations and publications meant this was an FME that hit its goals while keeping industry engaged. In particular, the well-integrity lab work has been a good stimulant for industry and we see potential in the coupled fluid-flow models."

- Philip Ringrose, Geoscience Specialist, Statoil

THE ROLE OF THE CENTRE

CCS has experienced turbulent times during the lifespan of BIGCCS. From optimism at the very start to a situation where support for CCS became scattered and hitting rock bottom around the mid-term review of the Centre. Since then, support for CCS has been growing and the latest IPCC reports and the Paris Agreement were important in the sense that they both essentially state that we cannot curb global warming to two degrees or lower without widespread use of CCS. BIOCCS is a fundamental condition to achieve these targets and that comes on top of massive CCS in industry, power and the fuel sector.

BIGGCS has been a stronghold for CCS R&D during these times and thus been instrumental in the progress of the topic during varying support for the concept of CCS. This shows the importance of thematic centres that can maintain such an activity regardless of the political and economic turmoils thus maintaining momentum and progress. Now CCS is much needed and BIGCCS has developed capacity and knowledge ready to be deployed for the national projects initiated for full scale CCS plants.

FUTURE PROSPECTS

Eight years of rewarding R&D activities is now over, but that does not mean we are slowing down. The results, experiences gained, and a new FME form the basis for new efforts.

The Norwegian CCS Research Centre

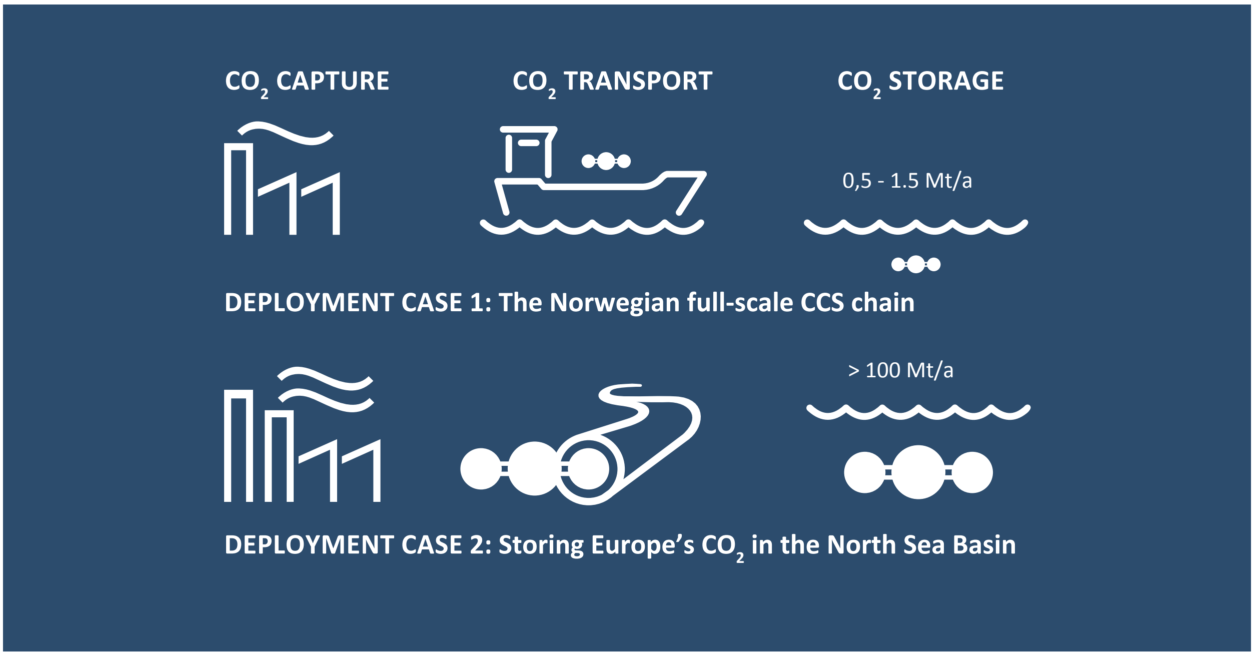
Through BIGCCS, a significant pool of knowledge, experience and resources – both people and infrastructure – was built. Eight years of meaningful activities has left us able to attack future challenges better prepared than ever before. Therefore, it was with great enthusiasm we received the news on May 26, 2016, that the proposed successor to BIGCCS, the Norwegian CCS Research Centre (NCCS), had been granted funding from the Research Council of Norway. This means that the CCS books will not be closed. Instead, new chapters will be added.

The plan is for NCCS to build on the knowledge and results developed in BIGCCS. However, the focus of NCCS is to fast-track CCS *deployment* in a dynamic and forward-looking approach that will capitalize on current and new knowledge to make CCS happen in time to meet the EU climate targets.

The NCCS network is significantly expanded compared to BIGCCS. While only one BIGCCS partner has decided not to continue in NCCS, several new partners have joined. It is especially motivating that several *technology providers* are among them. With a few still on the waiting list, the following industry companies and research institutes have joined NCCS:

Companies:
Aker Solutions AS, ANSALDO Energia, A/S Norske Shell, CoorsTek Membrane Sciences AS, Gassco AS, GE Energy, Norcem, Krohne Ltd, Larvik Shipping AS, Norwegian Oil and Gas, Municipality of Oslo, Quad Geometrics Norway AS, Statoil ASA, and TOTAL E&P Norge AS.

Research Institutes:
British Geological Survey, Norwegian Geotechnical Institute, Norwegian University of Science and Technology, Ruhr-Universität Bochum, SINTEF, TNO,



Technische Universität München, University Centre at Svalbard, University of Oslo, University of Western Australia, and Universität Zürich.

Expansive Plans

With an annual budget of NOK 50 million, FME NCCS will have the resources to tackle the problem head-on, but the ambition is so much bigger. There is a clear strategy to expand NCCS activities with spin-off projects, especially EU-funded projects. The NCCS consortium has already applied for several EU projects under the Horizon 2020 programme, and new possibilities will be sought out in the years to come.

More innovation focus

With deployment as the central issue in NCCS, the focus on innovation will be stronger. NCCS industry partners will assume an even more hands-on role to ensure return on investments. The new Centre will promote open innovation processes and encourage bi-lateral cooperation with each partner on their ideas and areas of interest.

The innovations developed in BIGCCS also represent great opportunities for continued activities. Many of the innovations are excellent candidates for product development that could reach the market and contribute in CCS deployment. The intention is to continue development of the innovations together with the BIGCCS partners, with the aim of bringing them to market.

On behalf of SINTEF and NTNU, the Norwegian CCS Research Centre will assume responsibility as organizer of the TCCS conference series. The conference will ensure visibility for the Centre, and will play an important role in maintaining the networking activities initiated by BIGCCS.

CONCLUSIONS

BIGCCS kept us busy, happy, concerned, optimistic, worried, on our toes, troubled, enthusiastic, sceptic, and passionate. But in conclusion, we are very satisfied!

No conflict in thinking wide

In terms of scope, FME BIGCCS came with a twofold challenge: Results were expected both in terms of *new and basic knowledge*, and in terms of *innovation*. We took this challenge, and we enjoyed it.

In summing up BIGCCS, Dr. Per Ivar Karstad (Statoil) said at the final Board meeting that the Norwegian full-scale project would not have been possible without the contributions of BIGCCS. He elaborated that the knowledge developed during the last eight years has been crucial in establishing the full-scale project, and that it will be essential in carrying out the project with proper quality.

A dual focus on *excellence in science* and on *innovation* might at first sound conflicting, but our experience is the opposite. By focusing on new and basic research, ideas for innovative products or processes often occur. BIGCCS has documented 46 such ideas (see page 33). The trick is to think about potential applications from the beginning. The innovations are at various stages on the TRL scale. Researchers will develop some of them further, while others are already at the disposal of the industry partners. Ultimately, it is up to the industry to take them to market.

It helps to be BIG

The long duration of an FME gives several advantages. The project is an excellent foundation from which new projects can be spun off and become part of the Centre activity. BIGCCS took this opportunity and added to its operation nine competence building projects (KPNs). The research partners were also granted several EU projects related to Centre activities. In this way, the BIGCCS umbrella of projects has increased from NOK 378 million to NOK 505 million during the Centre period, and returned to the partners more than they could have expected at the beginning.

The creation of strong and lasting networks – both nationally and internationally – is another upside. With projects lasting this long, individuals and organisations are willing to invest more time and resources to develop lasting relations that in the end can foster new opportunities and generate closer project cooperation.

BIGCCS organized the TCCS Conference three times, and was the single largest project contributor to the last three GHGT conferences. One effect of such visibility is that the Centre partners have become increasingly popular as partners in new project applications. Managed with shrewdness, this is a valuable asset for the future.

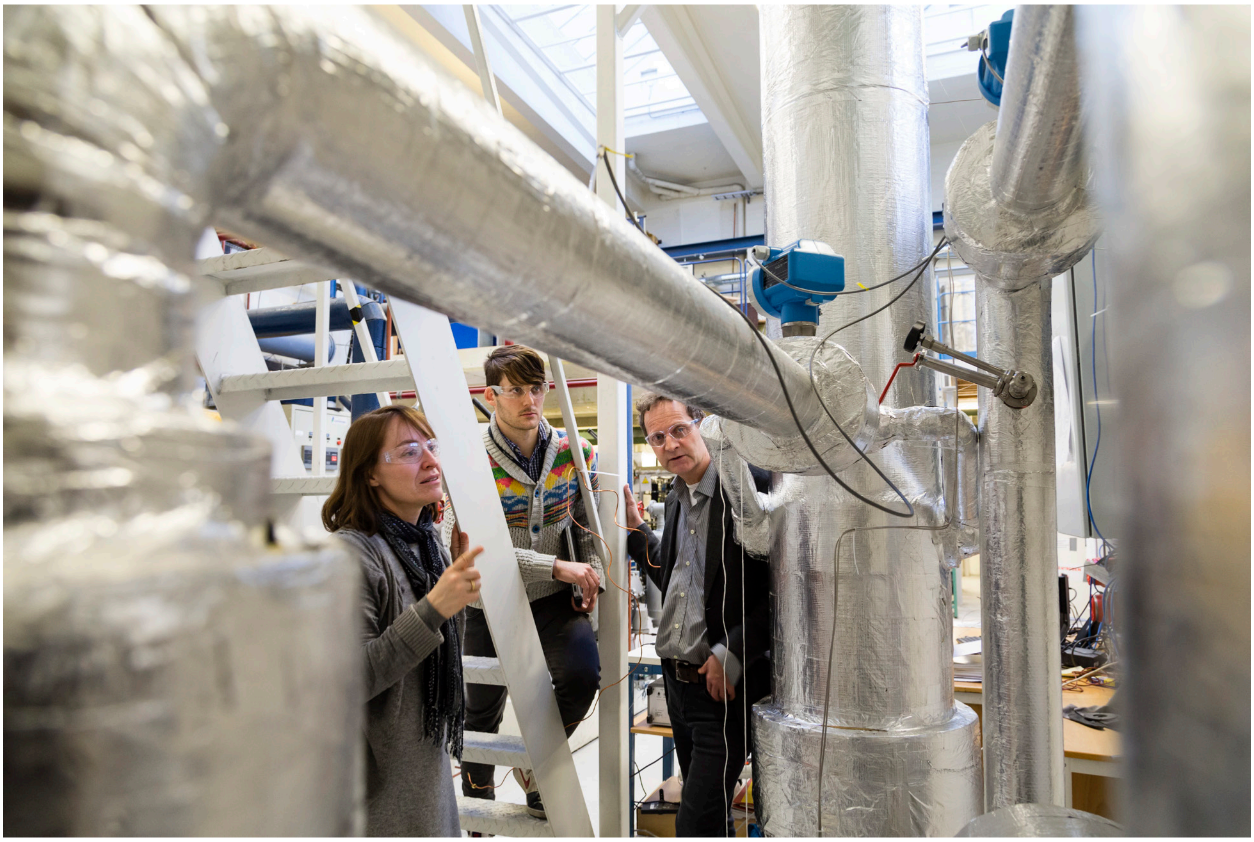
BIGCCS work was set up with three diciplinary sub-projects (capture, transport and storage) and one cross-disciplinary value chain project. To avoid becoming a group of silos, we actively encouraged cross-disciplinary activities and created arenas where researchers from all disciplines could meet. Consortium days, workshops and seminars were all successfully used to increase interaction between the disciplines. A positive effect is a shorter road to the optimal results.

A key element in the operations of the Centre was a forward leaning and dedicated management group. The CMG kept a close eye on operations and developments, and acted as an effective decision-making body. With just a handful of exceptions, the CMG met every two weeks throughout the eight years of the Centre. We believe that this 'hands-on' philosophy of continuity was an important success factor.

… and some learning

Except for a reorganization of activities resulting from the midway evaluation in 2014, Centre activities were carried out in accordance with the research plan as presented in the application. An advantage of this was predictability in terms of planning for the researchers. On the other side, we see in the aftermath that it could also have been an advantage to build in a little more flexibility to adjust the plans during the Centre. This is learning we will take forward into the FME NCCS.

BIGCCS has enjoyed and greatly benefitted from a high degree of involvement from the industry partners. Partners took an active role in developing plans and came together to discuss their applications and their results. We found it extremely useful to use webinars as a means to involve individuals from all levels in partner organizations. This is a cheap and efficient way of connecting with people, who will generate enthusiasm and engagement within the partner organizations. NCCS will continue to exploit the benefits from hosting such webinars.



Kristin Jordal, David Berstad and Petter Nekså inspecting laboratory experiments.

APPENDIX

Cost

Sub-program	SINTEF ER	BGS	CICERO	NGU	GEUS	NTNU Samfunns-forskning	NTNU
CO_2 Capture (SP1)	56 032 986						
CO_2 Transport (SP2)	25 800 000						
CO_2 Storage (SP3)		13 799 404		2 359 360	17 827 264		
CO_2 Value Chain (SP4)	14 417 600		3 335 991				
Academia							68 422 050
Equipment	1 446 875						
Management & Centre buidling	32 010 379					3 911 637	
Sum	129 707 840	13 799 404	3 335 991	2 359 360	17 827 264	3 911 637	68 422 050
Sub-program	**DLR**	**Stiftelsen SINTEF (SINTEF M&C)**	**SINTEF PR**	**DNV**	**UIO**	**TUM**	**Total**
CO_2 Capture (SP1)		52 052 389					108 085 375
CO_2 Transport (SP2)		15 200 000					41 000 000
CO_2 Storage (SP3)			53 060 993				87 047 021
CO_2 Value Chain (SP4)				1 793 994			19 547 585
Academia	4 507 646				5 431 020	5 427 566	83 788 283
Equipment							1 446 875
Management & Centre buidling							35 922 016
Sum	4 507 646	67 252 389	53 060 993		5 431 020	5 427 566	375 043 161

Funding

Contributor	Cash	In-kind	Total
ConocoPhillips	12 750 000		12 750 000
Gassco AS	20 000 000		20 000 000
ENGIE (former GDF SUEZ)	20 000 000		20 000 000
Shell Technology Norway AS	17 750 000		17 750 000
Statoil Petroleum AS	17 750 000		17 750 000
TOTAL E&P Norge AS	17 750 000		17 750 000
Aker Solutions AS	4 500 000		4 500 000
Statkraft Development SF	3 000 000		3 000 000
Det Norske Veritas AS	2 000 000	1 793 994	3 793 994
Hydro Aluminium AS	6 000 000		6 000 000
BGS		7 025 089	7 025 089
CICERO		686 715	686 715
DLR		2 316 012	2 316 012
GEUS		10 759 106	10 759 106
NGU		1 181 360	1 181 360
NTNU		11 197 689	11 197 689
NTNU Samfunnsforskning AS		561 025	561 025
SINTEF Energi AS		21 441 931	21 441 931
SINTEF Petroleumsforskning AS		13 643 560	13 643 560
Stiftelsen SINTEF (M&C)		17 992 631	17 992 631
TUM		1 230 670	1 230 670
UiO		3 713 379	3 713 379
Research Council of Norway	160 000 000		160 000 000
			375 043 161

KPN projects (NFR/CLIMIT) amended to BIGCCS

Acronym	Full project titles	Financing (NOK)
CO_2Mix	Experimental investigations of selected thermophysical properties of CO_2 relevant for CCS	26,000,000
BIGCLC Phase II	Large-scale demonstration of pressurized Chemical Looping Technology (CLC) in natural gas power generation with CO_2 capture – Phase II	21,600,000
CAMPS	Cross-Atlantic combustion modeling, programing and simulation	12,000,000
FEFRock	Fundamental effects of CO_2 on rock properties	9,600,000
BIGCLC Phase III	Large-scale demonstration of pressurized Chemical Looping Technology (CLC) in natural gas power generation with CO_2 capture – Phase III	14,500,000
HyMemCOPI	Novel hybrid membranes for post-combustion CO_2 capture in power plants and industry	7,000,000
SINTERCAP	Shaping of advanced materials for CO_2 capture processes	7,200,000
Well integrity	Ensuring integrity during CO_2 injection	7,200,000
uniCQue	Uncertainty reduction in monitoring methods for improved CO_2 quantity	6,400,000

Post doctoral researchers with financial support from the Centre budget

Name	M/F	Country	Scientific area	Period	Scientific topic	Main contact
Anwar Bhuiyan	M	Bangladesh	CO_2 storage	2010–2011	Advanced geophysical monitoring	Martin Landrø, NTNU
Hassan Karimaie	M	Iran	CO_2 storage	2010–2012	Experimental studies of diffusion/ convection of CO_2 in aquifers	Ole Torsæter, NTNU
Xiangping Zhang	F	China	CO_2 value chain	2011–2013	Extended value chain analysis of CCS	Truls Gundersen, NTNU
Nousha Kheradmand	F	Iran	CO_2 transport	2012–2013	Coupled structure-fluid model for cracking in pipes	Christian Thaulow, NTNU
Chao Fu	M	China	CO_2 capture	2012–2014	Integrated assessment and oxy-combustion	Truls Gundersen, NTNU
Rahele Farokhpoor	F	Iran	CO_2 storage	2012–2014	Effects of CO_2 on rock properties	Ole Torsæter, NTNU
Vincent Thoréton	M	France	CO_2 capture	2014–2016	Chemical Looping Combustion Technologies	Kjell Wiik, NTNU
Nicolaine Agofack	M	Cameroon	CO_2 storage	2015–2017	Acoustic core measurements and two-phase flow	Rune Holt, NTNU

PhDs with financial support from the Centre budget

Name	M/F	Country	Scientific area	Period	Thesis title	Main advisor
Alexandre Morin	M	France	CO_2 transport	2009-2012	Mathematical modeling and numerical simulation of two-phase multi-component flows of CO_2 mixtures in pipes	Inge Gran, NTNU
Andrew North	M	USA	CO_2 capture	2010-2013	Experimental investigations of partially premixed hydrogen combustion in gas turbine envirnments	Robert W. Dibble, UC Berkeley
Don Frederick	M	USA	CO_2 capture	2010-2013	Numerical investigations of a hydrogen jet flame in a vitiated coflow	Jyh-Yuan Chen, UC Berkeley
Georg Baumgartner	M	Germany	CO_2 transport	2010-2014	Experimental investigations of hydrogen flashback behavior in turbulentboundary layers	Thomas Sattelmayer, TUM
Rafael Antonio Sánchez	M	Argentina	CO_2 capture	2010-2014	Modeling and simulations of sorption-enhanced steam methane reforming (SE-SMR) operated in circulating fluidized bed reactors	Atle Hugo Jakobsen, NTNU
Vajiheh Nafisi	F	Iran	CO_2 capture	2010-2014	Development of mixed matrix membranes for carbon dioxide capture	May-Britt Hägg, NTNU
Amir Taheri	M	Iran	CO_2 storage	2010-2015	Study of density-driven-natural-convection (DDNC) mechanism in CO_2 sequestration in heterogeneous and anisotropic brine aquifer	Ole Torsæter, NTNU
Xinzhi Chen	M	China	CO_2 capture	2010-2013	Dense oxygen separation membrane materials - Thermal and chemical expansion of $La_{1-x}Sr_xMO_{3-d}$ and tape casting and mechanical properties of La_2NiO_{4+d}	Tor Grande, NTNU
Sissel Grude	F	Norway	CO_2 storage	2010-2014	Geophysical monitoring of CO_2 storage in the subsurface	Martin Landrø, NTNU
Einar Vøllestad	M	Norway	CO_2 capture	2010-2014	Mixed proton electron conducting oxides as hydrogen transport membranes in electrochemical potential gradients	Reidar Haurgsrud, UiO
Xiaoguang Ma	F	China	CO_2 capture	2010-2014	Precipitation in carbon dioxide capture processes	Jens-Petter Andreassen, NTNU
Mansour Soroush	M	Iran	CO_2 storage	2010-2014	Simulation and experimental investigation of different phenomena in CO_2 storage in the saline aquifers	Jon Kleppe, NTNU
Robin Wegge	M	Germany	CO_2 transport	2010-2016	Speed of sound and density measurements of binary, CO_2-rich mixtures over a wide temperature and pressure range	Roland Span, RUB
Nina Enaasen Flø	F	Norway	CO_2 capture	2011-2015	Modelling and analysis of process dynamics related to post-combustion CO_2 capture	Magne Hillestad, NTNU
Rengarajan Soundararajan	M	India	CO_2 capture	2011-2015	Coal based power plants using oxy-combustion for CO_2 capture: Process integration approach to reduce capture penalty	Truls Gundersen, NTNU
Espen Birger Raknes	M	Norway	CO_2 storage	2011-2015	3D elastic time-lapse full waveform inversion	Børge Arntsen, NTNU
Marcin Dutka	M	Poland	CO_2 capture	2012-2015	Studies of low NO_x burner technology	Terese Løvås, NTNU
Snorre Foss Westman	M	Norway	CO_2 transport	2013-2016	Experimental investigation of phase equilibria of CO_2 mixtures relevant for CCS	Ivar Ståle Ertesvåg, NTNU
Vera Hoferichter	F	Germany	CO_2 capture	2013-2017	Experimental investigations on the influence of acoustic excitations on flame flashback during premixed hydrogen combustion in a model burner	Thomas Sattelmayer, TUM
Dawid Szewczyk	M	Poland	CO_2 storage	2012-2017	Rock physics and geomechanical aspects of seismic monitoring of CO_2 storage in the subsurface	Rune Holt, NTNU
Gabriel Guerrero Heredia	M	Mexico	CO_2 capture	2014-2017	Novel Hybrid Membranes for Post-Combustion CO_2 Capture	May-Britt Hägg, NTNU

PhDs without financial support from the Centre budget

Name	M/F	Country	Source of funding	Scientific area	Period	Thesis title	Main advisor
Christian Eichler	M	German	BIGCO2 project	CO_2 capture	2007-2011	Flame flashback in wall boundary layers of premixed combustion systems	Thomas Sattelmayer, TUM
Szczepan P. Polak	M	Poland	BIGCO2 project	CO_2 storage	2007-2014	Laboratory and numerical study of scaling parameters used in modeling of CO_2 storage in rocks	Ole Torsæter, NTNU
Camilla K. Vigen	F	Norway	University of Oslo	CO_2 capture	2009-2014	Novel mixed proton electron conductors for hydrogen gas separation membranes	Reidat Haugsrud, UiO

PhDs completing their project in 2017-2018

Name	M/F	Country	Scientific area	Period	Thesis title	Main advisor
Sohrab Gheibi	M	Iran	CO_2 storage	2013-2017	Geomechanical Modelling of CO_2 Injection and Storage	Rune Holt, NTNU
Christoph Meraner	M	Germany	CO_2 capture	2015-2018	Investigation of scalability of low NOx combution technology	Terese Løvås, NTNU

MSc students with thesis related to CCS

CO_2 Capture (SP1)

Name	M/F	Country	Semester	Full Title	Supervisor
Helene Østby	F	Norway	Spring 2010	Dynamic modelling and simulation of a CO_2 capture plant	Magne Hillestad
Matthieu Dreillard	M	France	Spring 2010	Energy Considerations around an amine CO_2 capture plant	Magne Hillestad
Vidar Graff	M	Norway	Spring 2011	Degydration and compression of contaminated CO_2 rich gas	Magne Hillestad
June Munkejord	F		Spring 2011	CO_2 capture in solutions with simultaneous precipitation of solids	Jens-Petter Andreassen
Henriette Næss	F	Norway	Spring 2013	New process configurations for post-combustion CO_2 removal	Magne Hillestad
Hilde Bråtveit Ekrheim	F	Norway	Spring 2013	Modeling and model identification of an equilibrium amine system - MEA and MDEA	Hallvard Svendsen
Elisabeth Børde	F	Norway	Spring 2014	CO_2 Capture from cement production	Magne Hillestad
Kine Hammersland	F	Norway	Spring 2014	Energy considerations around an amine CO_2 capture plant	Magne Hillestad
Espen Tjønne-land Wefring	M	Norway	Spring 2011	Nano-structuring of oxygen permeable membrane by chemical etching techniques	Kjell Wiik
Julia D. Meyer	F	Norway	Spring 2011	Processing and mech. props. of tape casted films with compositions $La_{0.2}Sr_{0.8}Fe_{0.8}Ta_{0.2}O_3$ as membranes for syngas production	Kjell Wiik
Runar Bøen	M	Norway	Spring 2012	An experimental investigation of co-sintering of oxygen permeable asymmetric membranes with compositions $La_{0.2}Sr_{0.8}Fe_{0.8}Ta_{0.2}O_3$	Kjell Wiik
Petter Wibe	M	Norway	Spring 2012	Optimisation of strength and permeability of tape castred poous substrates with composition $La_{0.2}Sr_{0.8}Fe_{0.8}Ta_{0.2}O_3$	Kjell Wiik
Nils Wagner	M	Norway	Spring 2012	Stability and permeation properties of asymmetric $La_{0.2}Sr_{0.8}Fe_{0.8}Ta_{0.2}O_3$ membranes for syngas production	Kjell Wiik

Name	M/F	Country	Semester	Full Title	Supervisor
Dan Lagergren	M	Sweden	Fall 2012	Oxygen permation in optimized, asymmertric LSFAl membrane for syn-gas production	Kjell Wiik
Frank Arne Glimastad	M	Norway	Spring 2013	Ceramic materials for oxygen separation membranes	Tor Grande
Silje Kathrin Nesdali	F	Norway	Spring 2013	Development of novel oxides for use in O_2 permeable membranes	Sverre M. Selbach
Belma Talic	F	Serbia	Spring 2013	Oxygen permation in optimized, asymmertric ceramic membranes for syngas production	Kjell Wiik
Birgitte Johannessen	F		Spring 2010	Numerica studies of flame propagation in channel flow	Terese Løvås
Jasmin Birkl	F	Germany	Spring 2011	Implementation and measurements on an exhaust gas analysing system	Anja Marosky / Thomas Sattel-mayer
Simon Bless	M	Germany	Fall 2011	Study of Cooling Air Injection at Gas Turbine Combustors with Large Eddy Simulation	Volker Seidel / Thomas Sattelmayer
Balbina Hampel	F	Germany	Spring 2012	Measurement of the Air Excess Ratio of an Auto-Igniting Flame by Means of Spectroscopy	Georg Tautschnig / Thomas Sattelmayer
Kjartan Juul Skarbø	M	Norway	Spring 2013	Operation study of low Nox burner technology	Terese Løvås
Nicolai Austarheim	M	Norway	Spring 2013	DNS simulations of acoustic instabilities in low emission combustion systems	Terese Løvås
Tobias Hummer	M	Germany	Fall 2013	3D conjugate heat transfer analysis of engine cylinder heads	Georg Baumgartner/ Thomas Sattel-mayer
Tore Hatleskog Zeiner	M	Norway	Fall 2011	Process Integration Potentials in Coal-based Power Plants	Truls Gundersen
Stian Tangen	M	Norway	Spring 2011	On the solution of the pellet and reactor model for SMR process using the methods of weighted residuals	Hugo A Jakobsen
Mohammad Ostadi	M	Iran	Spring 2013	Surrogatye Models for Integrated Reforming CC Optimization	Rahul Anantharaman
Erik Lien Johnesen	M		Spring 2011	Optimization-based desigen of an IRCC process	Truls Gundersen
Elmir Sisic	M	Croatia	Fall 2012	Utilization of low temperature heat in coal-based power plants with CO_2 capture	Truls Gundersen
Katrin Finke	F	Germany	Fall 2014	Development and validation of a Matlab algorithm to detect flame front from OH-PLIF and PIV images of a turbulent, premixed hydrogen flame	Georg Baumgartner/ Thomas Sattelmayer
Linn-Therese Forthun	F	Norway	Spring 2015	Simulation and model verification of the dynamic and steady state behavior of the CO_2 capture plant at TCM	Magne Hillestad
Severin M. Reiz	M	France	Spring 2015	CFD simulations of low Nox burner	Terese Løvås
Kristin Skrebergene	F	Norway	Spring 2015	New technologies for carbon capture in hydrogen production from fossil fuels	Truls Gundersen
Opeyemi Bamigbetan	M	Nigeria	Spring 2015	A systematic degign methodology for multicomponent membrane systems	Truls Gundersen
Gina Plathe Helsing	F	Norway	Spring 2015	Options for carbon capture with storage or reuse in waste incineration processes	Truls Gundersen

CO_2 Transport (SP2)

Name	M/F	Country	Semester	Full Title	Supervisor
Nicolas Morin	M	France	Fall 2010	Coupled fluid-structure model used for modelling of running fracture in ductile steel pipelines	Håkon Ottar Nordhagen
Gjermund Haug	M	Norway	Spring 2011	Running fracture in a H2 pressurized pipeline: From small scale material testing to full scale experiments and simulations	Håkon Ottar Nordhagen
Steffen Valheim	M	Norway	Spring 2011	Running fracture in a H2 pressurized pipeline: Characterization and simulation of dynamic ductile fracture in two X65 pipeline steels	Håkon Ottar Nordhagen
Alexander Maurer	M	Germany	Spring 2014	Commissioning of a single-sinker densimeter and first measurements in CO_2 rich binary mixtures	Robin Wegge
Aleksander Reinertsen	M	Norway	Spring 2015	Models and numerical methods for two-pase flow of CO_2 in pipes	Svend Tollak Munkejord

CO_2 Storage (SP3)

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

Peer reviewed articles

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5. ANANTHARAMAN, R., BERSTAD, D. O. & ROUSSANALY, S. 2014. Techno-economic performance of a hybrid membrane – Liquefaction process for post-combustion CO_2 capture. *Energy Procedia,* 61, 1244-1247.
6. ANANTHARAMAN, R. & GUNDERSEN, T. 2016. A new paradigm in process synthesis focus on design of power plants and industrial processes integrated with CO_2 capture. *Computer-aided chemical engineering,* 38, 1189-1194.
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