

Gas Technology
Centre

Gassteknisk
senter

2003

2019



GLOSSARY

ECCSEL ERIC: The European Commission's European Carbon Dioxide Capture and Storage Laboratory Research Infrastructure

FME: Centre for Environment-Friendly Energy Research

GHGT: Greenhouse Gas Control Technologies Conference

RCN: Research Council of Norway / Forskningsrådet

SFI (CRI): Centre for Research-Based Innovation

TGTC: Trondheim Gas Technology Conference

TCCS: Trondheim CCS Conference

NOTE: Equinor has been involved throughout the lifetime of the centre and was known as Statoil and StatoilHydro at various times. For clarity, we have used the name Equinor throughout the report.

The End Is Only The Beginning

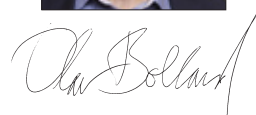
Climate change has become a major issue throughout the lifetime of the centre. Natural gas is a vital transition fuel in the green transition to a low-carbon economy. While global politicians debate the best ways to meet the goals of the Paris Agreement, the need to develop technology and methods along the gas value chain has never been higher.

Since its creation in 2003, the Gas Technology Centre (GTS) provided an essential platform for cooperation across NTNU, SINTEF and Equinor. Although the centre's goals changed throughout its life, there was always a focus on developing a thriving research ecosystem for gas technologies. This included promoting collaboration and cooperation, lobbying for funding programmes, creating project applications in focus areas, and funding education to ensure a steady flow of the next generation of gas technology researchers.


In this report, we've chosen to look back at a few of the success stories to show what is possible when universities, research institutes and the private sector come together to work on shared societal interests.

The gas technology expertise developed under GTS can go on to contribute towards the transition to a low carbon future. The centre's legacy will live on, not just in the physical infrastructure now in place but also in the spirit of collaboration and cooperation that must continue if we are to achieve a successful green transition.





Olav Bolland
Dean, Faculty of Engineering
NTNU




Inge Røinaas Gran
CEO, SINTEF




Sophie Hildebrand
Chief Technology Officer,
Senior Vice President
Research & Technology
(R&T), Equinor

Inspecting a deep sea compressor
Photo: Geir Mogen/NTNU

Then and Now



Today, Trondheim is seen as a leading European capital for gas research. But things never used to be that way. To understand the impact of a centre that spanned so many years, it's best to take a step back and look at the bigger picture.



// It seemed appropriate that the person to 'light the flame' at the GTS opening ceremony should be the man whose comments spurred the creation of GTS. The then Norwegian Minister of Petroleum and Energy Einar Steensnæs used a loaned Olympic torch, nine years after Lillehammer hosted the Winter Games. In the run-up to those Games, NTNU Energy's Johan Hustad contributed research and expertise on gas flames to keep Crown Prince Håkon safe as the world watched the opening ceremony.





Opening of the LowEmission centre in June 2018.

There is now a family of researchers across the three partners that know each other very well.

At the turn of the century, natural gas engineering research was taking place in Trondheim. But projects were relatively small and to a large extent independent of one another. It was a fractured research environment with few synergies.

The problem became clear when in 2002, the Norwegian Minister of Petroleum and Energy Einar Steensnæs launched a proposal to establish an exhaust gas technical centre near Haugesund. He was not familiar with the scale of gas engineering research at NTNU and SINTEF and the potential for further development. A more joined-up approach was needed to put Trondheim's gas research community on the map, so that future opportunities would not be missed.

Around the same time, Professor Bjarne Foss led the project 'Process Systems Engineering – From Natural Gas to Energy Products', to a successful grant from the Research Council of Norway. The work that went into the application for this Strategic University Project (SUP) shone a

spotlight on the potential for deeper interdisciplinary and coordination between NTNU and SINTEF in the gas technology world.

It wasn't just the academic world that saw the potential in such a collaboration. Statoil (now Equinor) had its research centre in Trondheim and were also surprised by the lack of recognition of the city. They joined GTS as a founding partner and remained committed to the centre throughout its life. To complete the loop, Einar Steensnæs was invited to the opening in April 2003.

A strategic platform for long-term thinking

The centre was always intended to be flexible and act as both a coordination point and catalyst for more specific

projects. The platform enabled the necessary strategic thinking required to secure funding for important long-term programmes. Thanks to the structured approach to open calls developed through the centre, NTNU and SINTEF became lead partners with the EU and achieved a huge success rate with grant applications

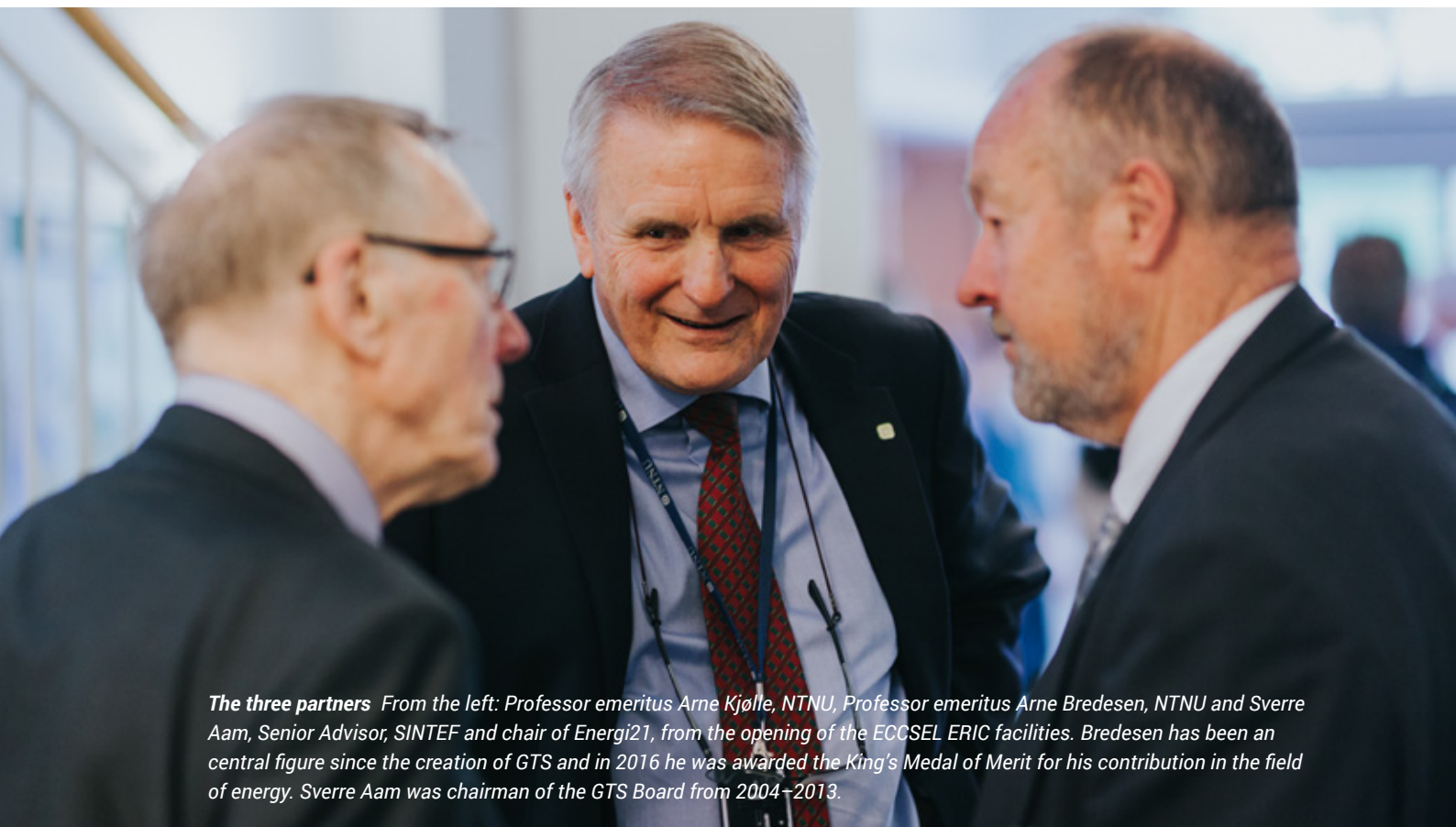
As you'll see from this report, much has happened in the subsequent 17 years since the establishment of GTS.

Major research projects including BIGCO2, SOLVIT, BIGCCS and NCCS have and still are achieving major results. Through the ENGAS and now ECCSEL network, research scientists from across Europe travel to Trondheim to make use of the city's extensive research labs. The number of researchers within the field has increased drastically. Many PhD positions were fully or partly-funded by GTS, while the centre played an important role in the creation of two International Master programmes in gas technologies at NTNU.

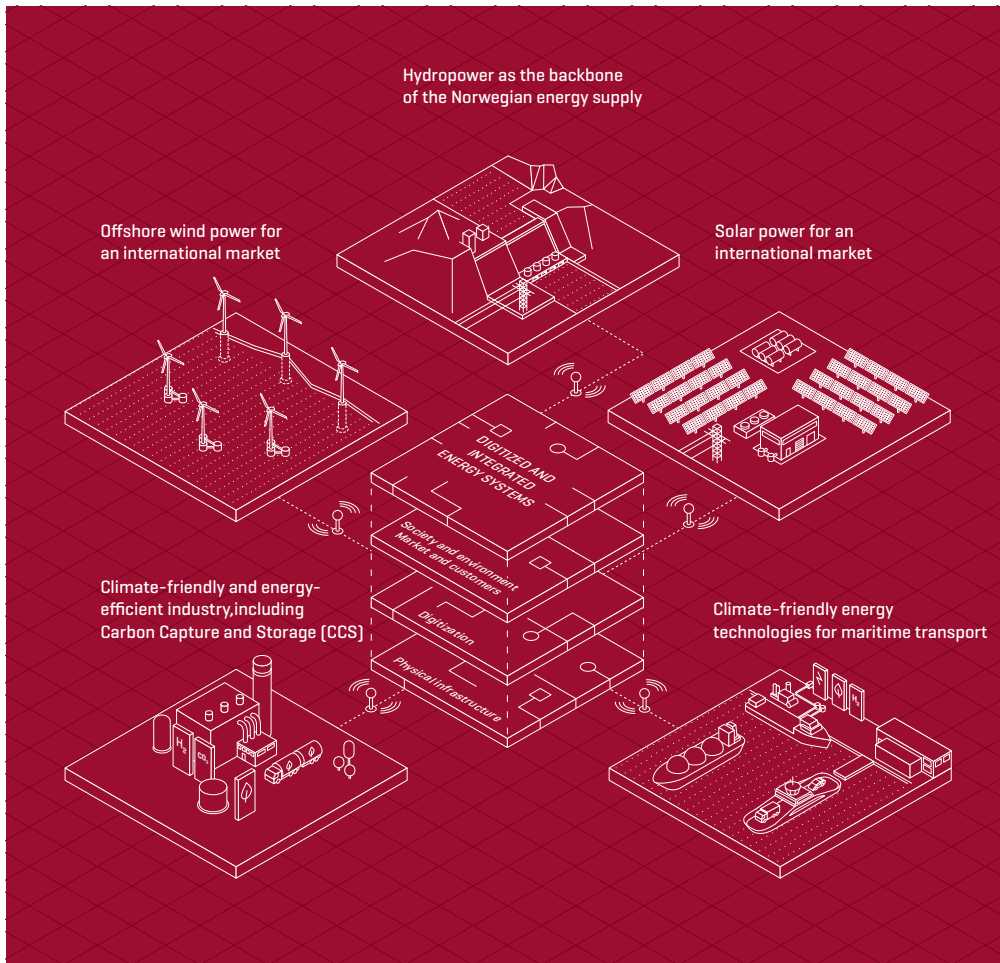
Experience to take forward

NTNU Professor Hilde Venvik explains that part of the motivation behind GTS was to promote the research work going on in Trondheim at NTNU, SINTEF and Equinor. "A lot of the funding went on communication and coordination to help launch initiatives that eventually resulted in successful proposals. Despite the ups and downs in the industry over the past two decades, this was a great success. There is now a family of researchers across the three partners that know each other very well."

The close collaboration between NTNU and SINTEF is now recognised internationally. In 2017, the Times Higher Education (THE) called out the NTNU-SINTEF partnership as the world's most prolific university-corporate partnership. As you'll read in the pages to come, there is no doubt that GTS played a key role in the partnership's success.



The three partners From the left: Professor emeritus Arne Kjølle, NTNU, Professor emeritus Arne Bredesen, NTNU and Sverre Aam, Senior Advisor, SINTEF and chair of Energi21, from the opening of the ECCSEL ERIC facilities. Bredesen has been an central figure since the creation of GTS and in 2016 he was awarded the King's Medal of Merit for his contribution in the field of energy. Sverre Aam was chairman of the GTS Board from 2004–2013.



// In 2008, the Norwegian Ministry of Petroleum and Energy established Energi21, a strategy for research, development, demonstration and commercialisation of new, climate-friendly energy technology. In its latest strategy document, Energi21 identifies climate friendly and energy-efficient industry including CCS as one of six key areas for investment and priority effort. The report states that a successful implementation of the strategy will require involvement from the business sector, research and educational institutions, and authorities. GTS has proved that such cooperation to deliver tangible results is possible.

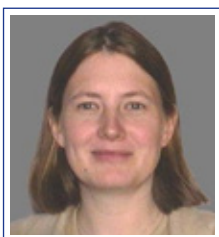
Because of GTS...

We asked several people involved with GTS over the years what the centre meant to them.



Nils A. Røkke, SINTEF

// GTS was not a typical centre. It was conceived as an accelerator with a small team that could work together, act strategically, and make decisions quickly to get projects and other centres off the ground. Equinor were the ideal partners for such a cooperation and were entirely aligned with our goals of increasing activity, education and visibility. The conferences and events hosted by GTS showed what can be achieved by working from a shared platform. SINTEF Director of GTS 2004–2008.



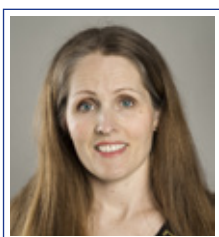
Siv Aasland, Equinor

// It was important to create a virtual centre to increase collaboration among several smaller groups working with gas technologies across NTNU and SINTEF, and create a common platform. The collaboration with Equinor on developing competence, educating new candidates and creating networking opportunities for gas technologies was and is very important for our industry. Representative of the board 2007–2010.



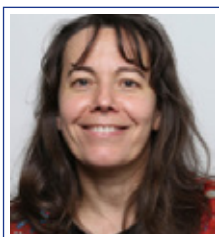
Olav Bolland, NTNU

// GTS contributed to improved cooperation between NTNU and SINTEF, and better coordination between different academic environments. This created new opportunities for funding both from industry and the Research Council. Today, interdisciplinary cooperation has become much better, but things were different back in 2003. GTS is an early example of developing collaboration across professional environments, which contributed to a more unified professional environment in natural gas. NTNU Director of GTS 2008.



Hilde Venvik, NTNU

// With so many shifting priorities in the industry, Equinor's follow-up was always professional. Their willingness to collaborate and look ahead was very good throughout the centre. GTS proved what can be achieved when industry and research truly collaborate. The competence built throughout GTS remains relevant, even when industry priorities change. NTNU Director of GTS 2009–14.



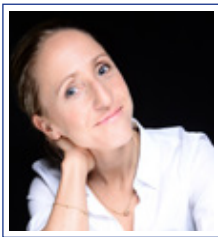
Maria Barrio, SINTEF

// To me, GTS was one of the first examples of the “power” of many. It was an umbrella for many research groups distributed across many corners of SINTEF and NTNU where everyone could feel ownership of a common goal. My motivation when leading the centre was striving to achieve the objectives (initiatives, conferences, seminars, etc) that none of the participants would have been able to achieve alone. SINTEF Director of GTS 2009–12.



Jon Magne Johansen, SINTEF

// An important legacy of GTS is the close bonds the centre formed between NTNU and SINTEF. We take those for granted today, but back at the beginning of GTS such relationships were highly dependent on individuals. GTS helped to pave the way for a much more structured approach to collaboration, and showed what was possible when these two great centres of research come together. SINTEF Director of GTS 2014–19.



Cecilie Gotaas Johnsen, Equinor

// Building more connections between industry and research institutions is crucial, but it's not just about training the next generation of problem-solvers. When the oil & gas industry hit a downturn in 2014, there was a lot of uncertainty in the industry, so the centre focused on the position of Norwegian gas in a wider context. The socio-political studies and reports we did then were important forerunners to the work of today with energy transition. GTS Board Representative from Equinor 2014–19.



Maria Fernandino, NTNU

// Through GTS it was possible to expose a whole generation of students to activities and challenges related to the focus areas of the centre and industry. This was performed via different mechanisms including annual student excursions to one of Equinor's gas processing plants in Norway, partial and full funding of PhD positions, financing of scientific equipment, and lunch seminars for dissemination. NTNU Director of GTS 2015–2019.



Ingvald Strømmen, NTNU

// GTS has over its 16 years contributed to bring up important and crucial new knowledge and candidates to the petroleum industry and public administration. These deliverables from NTNU and SINTEF has been enablers to strengthen competitiveness of businesses. The new candidates educated has been important for recruitment of employees to the sector. Chairman of the Board 2016–19.



Sverre Quale, Director ECCSEL

// Having the ECCSEL infrastructure in place means so much to the research community both here in Trondheim and internationally. Without the fundamental and scale-up research done at these world-class labs, the technology could never have been commercialised so fast. The investment in the labs – which GTS played a big part in – is being paid back many-many times.

Highlights

2003

Opening ceremony followed by a national seminar with 90 attendees

2004

- Coordination of project applications with RCN
- Beginning of 10-year funding of Professor position in Hydrogen technologies

2005

- Development of EU & RCN project proposals, including development of the BIGCO2 project

2006

- New CRI for e-field and Integrated Operations
- Hosted the international conference GHGT-8
- Launch of the BIGCO2 project

2007

- GASSMAKS research programme launched
- Preparation for the Seventh Framework Programme

2013

- Development of proposal for SFI Remote Gas
- Strategy work on national gas technology research programme

2012

- Strategy shift to the natural gas value chain
- Support for LNG and gas-to-liquids projects

2015

- SFI SUBPRO: Subsea Production and Processing
- SFI iSCI: Industrial Catalysis Science and Innovation

2011

- Hosted 2nd Trondheim Gas Technology Conference
- Gas Technology activities report produced

2016

- NCCS: Norwegian CCS Research Centre

2010

- Organised IEA Summer School in Svalbard
- Support for Biomass to Liquid Fuels project

2009

- Trondheim Gas Technology Conference established
- A GREEN Sea R&D project awarded funding
- Gas Technology activities report produced
- BIGCCS: International CCS Research Centre

2017–19

- Hosted 3rd & 4th Trondheim Gas Technology Conferences
- Support for LNG & hydrogen projects
- Continuation of education and student visit programmes

2008

- Support for ECCSEL lab infrastructure programme
- SOLVit project launched
- Two new NTNU International Master programmes



A Flexible Accelerator for Gas Technologies

Throughout the centre's life, there has been a substantial shift in gas prices, political priorities, industrial demand and more. The flexibility of GTS allowed it to support these shifting priorities by acting as a springboard for more deeper research.



Internship student Ranisha S. Sitlapersad from Suriname and University of Twente adjusts on one of the samplers of the CO₂ Mix phase equilibrium setup.

The centre brought 350 research scientists into an umbrella organisation to improve visibility, aid coordination, create new R&D initiatives, promote gas technology education and address gas technologies as a national priority.

“GTS was established in part to steer research priorities and act as a catalyst for the creation of large, more in-depth programmes. While it was impossible to predict the industry changes that would occur in the years to come, the decision to create a flexible centre certainly paid off,” explains SINTEF Executive Vice President Sustainability, Nils Røkke.

Building wider competence in natural gas technology R&D

In many ways, GTS was a natural successor to the national gas research program SPUNG. There was a need to fill the hole left by SPUNG’s closure in order to build broad competence and infrastructure, and this was the focus during the early years of GTS.

One major success of GTS funding was the planning work that went into the creation of a Norwegian Research Council programme for gas technologies. The programme GASSMAKS gave the opportunity not only for NTNU and SINTEF but the wider Norwegian research community to look at value creation possibilities from natural gas.

GTS funding was also instrumental in the ENGAS infrastructure project, which provided vital laboratory equipment at Gløhaugen and other places in Norway to facilitate research in the decades to come. The ENGAS infrastructure would go on to become the Norwegian base of the ECCSEL ERIC, a pan-European research infrastructure for CCS technologies.

In addition to the infrastructure, GTS prioritised the funding of educational programmes. This included planning and development support for two new NTNU International Master programmes related to gas technologies. Equinor were especially interested in the educational aspect of the centre, and their support was used to host student visits to Equinor plants and to fund many PhD’s over the life of the centre.



Another early achievement was the planning and hosting of the IEA Conference on Greenhouse Gas Control Technologies (GHGT-8) in 2006. During the four-day event attended by almost 1,000 participants from 47 countries, hundreds of technical papers and posters were presented. It was the largest CCS conference to date. To bring such a high-profile industry event to Trondheim in the early years of the centre helped to verify the city's position as a leader in gas technology research.

A political voice

GTS also gave experts from NTNU, SINTEF and Equinor an ongoing political platform to help shape future energy policy based on research findings. Throughout the centre's life, GTS representatives met with politicians through several channels.

In 2009, SINTEF and GTS hosted the European Economic Area Joint Parliamentary Committee Meeting on CCS and offshore wind technology. Around 45 participants from the European Free Trade Association (EFTA) and the

Norwegian Parliament took part in the programme, which included visits to the wind turbine lab at Gløshaugen and the Tiller Multiphase and CO₂ labs. Equinor gave presentations about the Sleipner and Snøhvit CCS experience.

Among other projects, the Ministry of the Environment sought feedback from GTS on the greenhouse gas emissions reduction document Klimakur 2020. The feedback covered the general approach of Klimakur and more specific comments on CCS, energy efficiency and gas as a substitute for coal.

CCS

During the early years of the centre, there was a societal consensus forming that the challenging EU climate targets could not be met without tackling waste CO₂ from large industrial plants. The substantial complexity of CO₂ capture, transport and storage needed substantial research work to lower barriers at every step of the process.

GTS played an active role in the creation of BIGCO2 and other projects that eventually led to the FME BIGCCS and its successor NCSS.



» Sintef-direktør på klimakonferanse i Polen



Nils Røkke, Executive Vice President Sustainability - SINTEF, is also the head of the European Research Alliance (EERA). He promotes sustainable energy solutions such as CCS and hydrogen in Norway and Europe. He attended COP24 in Katowice where he presented solutions toward a zero emission society, as featured in Adresseavisen 15. December 2018.

Kom til Katowice med løsninger

- Vi har teknologi som kan bringe oss ned mot nullutslippssamfunnet. Men da må vi fortsette å utvikle teknologien og ta den i bruk i stor skala.

i Polen
GRETE HOLSTAD 92198762
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»Katowice
Klima-konferanse

FNs klimakonferanse i Katowice handlet det ikke bare om temperaturer og konsekvenser for natur og mennesker av global oppvarming. Mange møter tok opp løsninger. En av dem som presenterte teknologiske løsninger, var Nils Røkke, Sintef's bærekraftsdirektør.

Det gjorde han blant annet på et møte i regi av International Emissions Trading Association (IETA), som organiserer noen av verdens største energiselskaper på jakt etter klimavennlige løsninger.

Du reklamerte for å bruke hydrogen som fossilfritt drivstoff, og du snakket om klimapanelets 1,5 grader-rapporten som en selvfølgelig premissleverandør. Det finnes de som stiller spørsmål ved konklusjonene i rapporten.

Vi må høre på vitenskapen og ikke på hva vi tror. I Sintef driver vi ikke med klimaforskning, men vi tar inn over oss faktaene som legges på bordet. Det er ingen grunn til å gamble. Det er skremmende at for hver gang det legges fram nye data, er det verre enn vi trodde.

Så du tror det er mulig å stanse den globale oppvarmingen?

Til en viss grad. Til to grader. Tida har løpt fra oss til å klare 1,5 grader. Men som forsker må jeg ta forbehold. Det finnes mekanismer menneskene ikke har kontroll over, som tining av tundraen i Sibir. Hvis det skjer, vil det slippe ut enorme mengder metan som er en mye verre klimagass enn CO₂. Det finnes flere slike sakalte tipping point, og hva gjør vi med det?

Ja, hva gjør vi?

Særlig innen sektorene energi, industri, transport og jordbruk finnes det teknologi som kan redusere utslippene betydelig. Og det er oppløftende for 90 prosent av utslippene kommer fra disse sektorene. Særlig energisektoren, den er enklest å dekarbonisere.

Hydrogen er altså en av

løsningene? Det du fortalte, så ut til å fenge forsamlingen.

Hydrogen kan brukes overalt i samfunnet. Innen transport, industri, til kraftproduksjon og oppvarming, og til å lagre energi. Den første hydrogen-hurtigbåten er snart ferdig, og hvis det er mulig å lage elly, er det i alle fall mulig med hydrogen-fly. Både båt og fly trenger drivstoff som backup til batteriene på lengre turer. Innen industrien kan ståler og jern framstilles med hydrogen i stedet for kull.

Hydrogen er ikke en energikilde, men bærer av energi og kan lagres. I kraftproduksjon kan hydrogen dermed brukes som energilagrer slik som vann, og brukes når vinden ikke blåser og sola ikke skinner.

Teknologien er altså tilgjengelig?

Den er tilgjengelig, men må optimaliseres for å bli mer effektiv og kostnadseffektiv. Hydrogen kan produseres fra elektrolyse eller naturgass med CO₂-fjerning. På Tjeldbergodden ligger de metanol fra naturgass via hydrogen. Det er fullt mulig å lage hydrogen fra naturgass samtidig som CO₂ fjernes. Men



Picture from left: Frederic Hauge, Managing Director of Bellona and Marie Bysveen, Senior Research Scientist at SINTEF presenting CCS at the European Parliament 12. November 2015.

// While it was impossible to predict the industry changes that would occur in the years to come, the decision to create a flexible centre certainly paid off.

To support the research work now taking place in other projects and centres, GTS returned to its priority of increasing visibility by hosting Trondheim CCS Conference (TCCS) and launching the Trondheim Gas Technology Conference (TGTC).

testing of H₂ technologies. Three proposals were also supported by the European Fuel Cells and Hydrogen Joint Undertaking. At the Technoport 2012 innovation conference, GTS supported Norway's first public trial of fuel cell vehicles.

Hydrogen

Once BIGCCS was up and running, there was less need for GTS to focus on CCS activities, although it still played a part with the organisation of conferences and other activities. However, the focus of the centre shifted more onto hydrogen.

Hydrogen technologies had already been a part of the GTS remit, not least because of Equinor's funding of an Associate Professor in Hydrogen technologies. Hilde Venvik held this position for five years before taking over as NTNU's GTS lead.

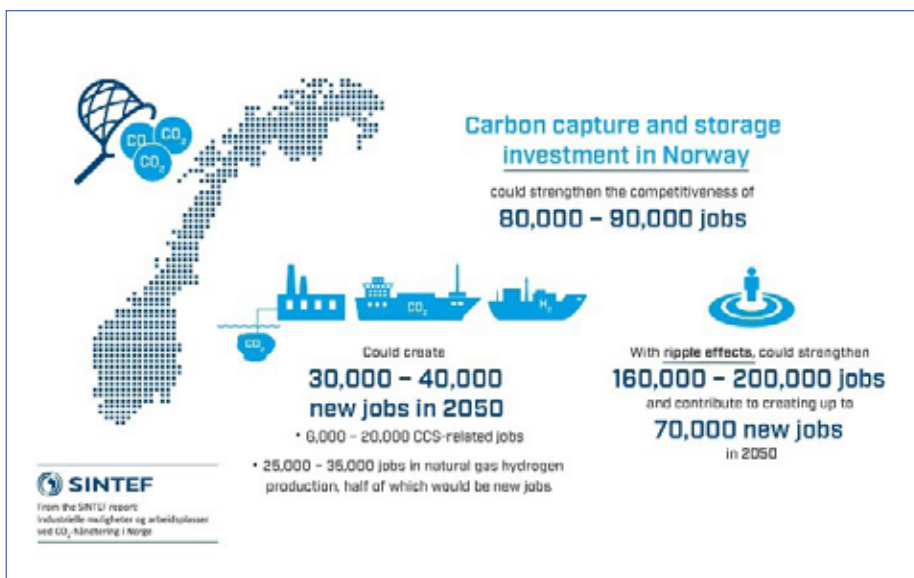
GTS co-sponsored the Norwegian Hydrogen seminar 2008 in Bergen, with Dr. Steffen Møller-Holst (SINTEF) and Prof. Edd Blekkan (NTNU) on the organising committee.

Several hydrogen and fuel cell proposals were given GTS support, including large-scale lab infrastructure for pilot

Natural gas processing and conversion

Significant work went into outlining a strategy for the third phase of GTS. This revised strategy put the natural gas value chain into focus, from gas resources and transport to processing, LNG and conversion. Equinor still supported GTS with participation and funding on a project-by-project basis.

The GTS budget was reduced during this time but key elements of the centre remained in place, from PhD funding and student excursions to the hosting of more gas technology conferences. The report *The Potential of Norwegian Natural Gas in a European Perspective* was produced to demonstrate how research along the natural gas chain can strengthen the Norwegian export position.



GASSMAKS

Maximizing Value Creation in the Natural Gas Chain.

The formation of a national R&D program for the industrial utilization of natural gas filled a desperately needed funding gap in the Norwegian natural gas ecosystem.

GTS played a critical role in the planning and initiation of the GASSMAKS research programme. Fronted by the Confederation of Norwegian Enterprise (NHO), the Norwegian Confederation of Trade Unions (LO) and Nork Gassforum, GASSMAKS aimed to increase the value creation from natural gas through industrial processing.

The programme was established in response to the conclusions of a report based on extensive dialogue between key Norwegian industries and the research community. Using resources from GTS, leaders from both SINTEF and NTNU were heavily involved in the development of this report on the need for a substantial R&D program on natural gas.

In the planning stage, GTS proposed research areas and received suggestions from other Norwegian research groups and firms through an open hearing. An important argument was that state-supported R&D in this area had been lacking since the end of the SPUNG research program in 1993.

NTNU and SINTEF went on to receive nearly half of the public funding available via GASSMAKS.

// As strategic partners to the core interest groups, SINTEF and NTNU provided crucial scientific information and lent legitimacy to the development of policy ideas.

– *Working Paper on Innovation Studies, University of Oslo*



Building on the Foundations

Throughout its long life, GTS laid the groundwork for many projects and centres with a more specific focus. Here are just a few.

SOLVit: Bringing solvents and technology from laboratory to industry

The aim of the eight-year SOLVit programme coordinated by Aker Solutions was to develop energy efficient and environmentally-friendly post combustion carbon capture systems for large-scale industrial CO₂ emissions. The programme increased the understanding of solvent based capture processes on both fundamental and industrial levels.



SOLVit Highlights:

TESTING: More than 80 different 1st generation solvents were characterised in laboratory test rigs at Sintef and NTNU, of which 8 solvent candidates (and MEA) were qualified for testing in pilot plants. More than 10 different 3rd generation solvents and concepts were investigated, resulting in 3 systems being selected for pilot plant testing.

METHODS: Several analytical methods were developed for specific groups of compounds. The build-up of analytical expertise and lab facilities during the course of SOLVit made it possible to analyse nearly 10,000 solvent samples from the different laboratory tests and pilot plant campaigns in the project.

SIMULATION: SINTEF developed a full flowsheet process simulator CO2SIM, a valuable tool for scale-up, process optimisation and design of full-scale carbon capture plants.

INFRASTRUCTURE: A pilot plant was established in Tiller, which provided the SOLVit project with a unique opportunity to test new solvent candidates in an early stage of development at realistic operating conditions, but in a well-controlled test environment. The plant was modified to include an acid wash system in order to allow for testing of more volatile solvent systems, then to allow for testing of 3rd generation solvents forming two liquid phases.

VALIDATION: Improvements in energy consumption relative to MEA of up to 35% improvement were demonstrated with novel solvents and process upgrades. The activity contributed significantly to mature the CO₂ capture technology of Aker Solutions and to mitigate risks related to scale-up and large-scale deployment.

EDUCATION: The educational programme contributed to developments within the areas of molecular modelling, mechanistic understanding of solvent degradation and development of 3rd generation solvent systems forming two liquid phases.

BIGCO2 – Building knowledge in CCS research

BIGCO2 was established with the ambition to take a big leap in CCS research. It started off with consultations with major companies that had a vested interest in CCS, developers, users and operators. For SINTEF, BIGCO2 consolidated much of the CCS R&D work being done across its institutes, thereby integrating capture, transport and storage into one research platform.

In the final report for BIGCO2, the Research Council of Norway said the project “contributed significantly to boost the knowledge and quality within CCS and bring Norway into a leading position within CCS development.”

BIGCO2 was also the basis for several EU FP7 projects and contributed to the quality of the applications within CCS, which had a remarkably success rate. Without the success of BIGCO2, there would have been no BIGCCS or NCCS, which have gone on to achieve solid results.



*Mona J. Mølnevik,
Research Director at SINTEF
and Centre Director at NCCS.*

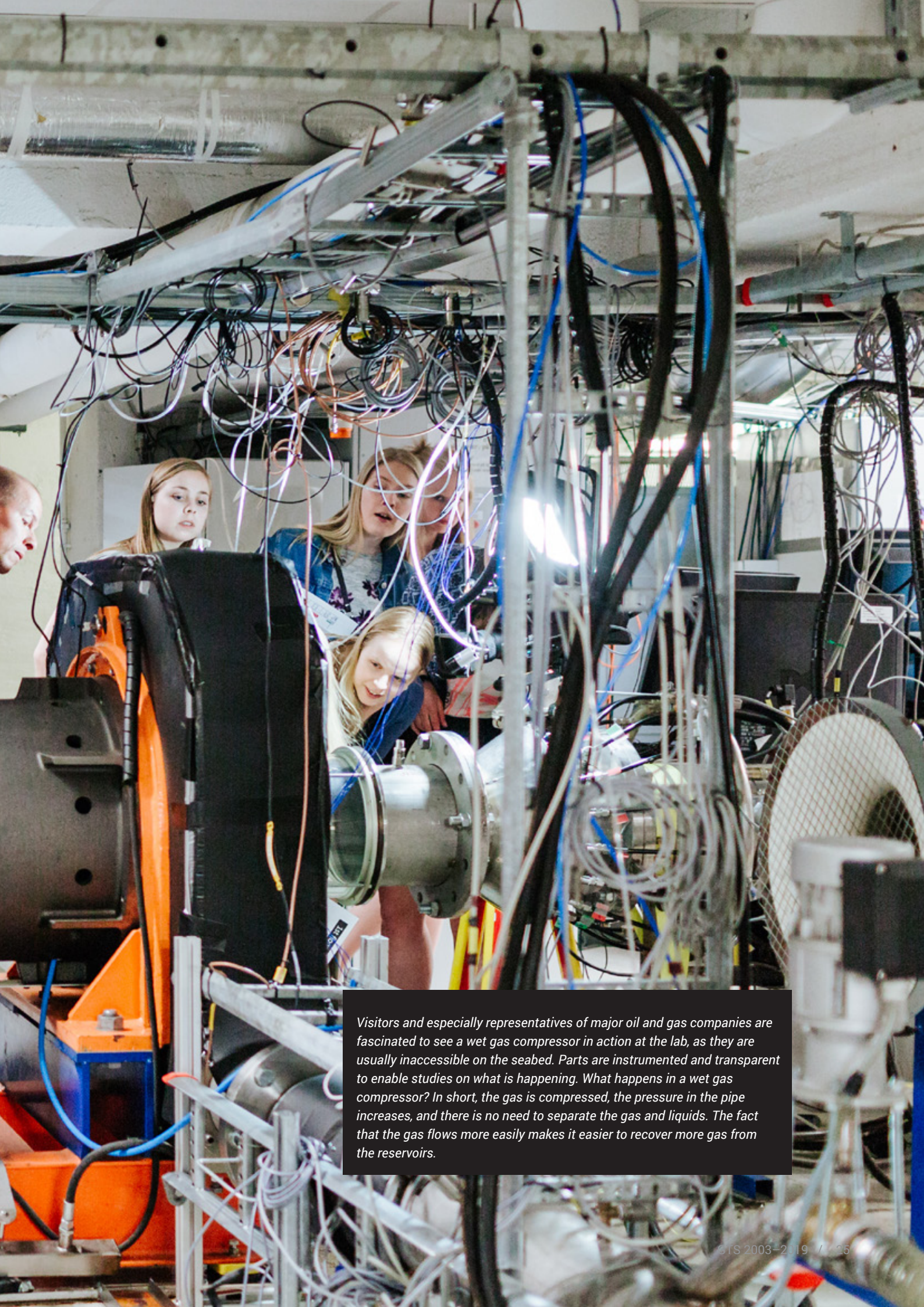
Main findings & achievement areas within BIGCO2

- High temperature membranes for clean power production
- Improved post-combustion capture by solvents development, systems modelling, simulations
- Pressurized combustion of enriched fuels
- Power cycle integration and analysis including unit modelling and simulation
- CO₂ chain analysis
- Enhanced oil recovery and safe underground storage of CO₂ in geological formations
- Chemical looping combustion
- Foundation for subsequent FME BIGCCS and FME NCCS

Developing a Lasting Infrastructure

The legacy of GTS: From campus research labs to a pan-European network

THE SWITCH



Visitors and especially representatives of major oil and gas companies are fascinated to see a wet gas compressor in action at the lab, as they are usually inaccessible on the seabed. Parts are instrumented and transparent to enable studies on what is happening. What happens in a wet gas compressor? In short, the gas is compressed, the pressure in the pipe increases, and there is no need to separate the gas and liquids. The fact that the gas flows more easily makes it easier to recover more gas from the reservoirs.

Today, Trondheim has one of the biggest concentrations of gas research labs and equipment in Europe. Together with the Netherlands, Italy, France and the United Kingdom, Norway operates ECCSEL, a European research infrastructure (ERIC) for CO₂ management research with its headquarters in Trondheim.

Norway is the first country outside the EU to lead a major European research infrastructure project.

The advanced scientific equipment in the areas of absorption technology, material technology, combustion technology, cryogenic processes and storage supports research that aims to cut emissions like CO₂, NO_x, SO_x and other greenhouse gases.

GTS played a major role in the FP6 funded Environmental Gas Management Research Infrastructure (ENGAS-RI), which ultimately led to the current ECCSEL ERIC network.

ECCSEL was put on the official European Strategy Forum on Research Infrastructure (ESFRI) roadmap in 2008 as the only new entrant in the energy theme. GTS supported the coordination work and search for funding.

“Initially this was just an NTNU/SINTEF collaboration and we felt it could and should be developed further. When the Norwegian Research Council approached us to propose new strategy areas for the ESFRI roadmap, the idea for ECCSEL was born,” explains NTNU’s Morten Grønli, who was involved in both ENGAS and ECCSEL.

The official opening of ECCSEL ERIC took place in 2016. Norway’s Secretary of State Ingvil Smines Tybring-Gjedde said the network was of great importance for the work on CO₂ management: “The infrastructure will help accelerate technology development for CO₂ capture and storage. This is technology we need to reach the climate goals of the Paris Agreement.”

Scientific goals of ECCSEL Norway:

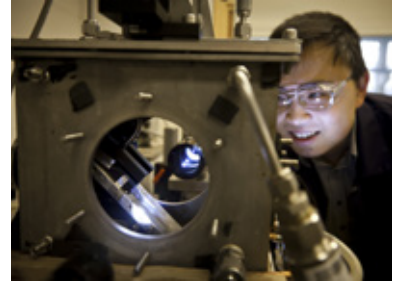
- Absorption
- Polymer membranes
- Advanced materials
- High-pressure oxy-fuel combustion
- CO₂ mixture characterisation
- Educational aspects

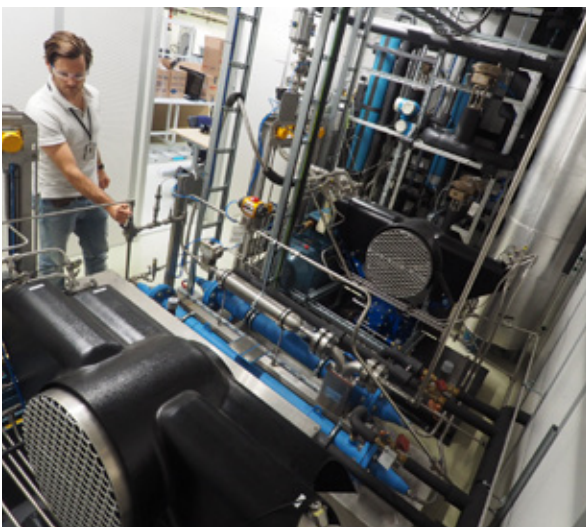
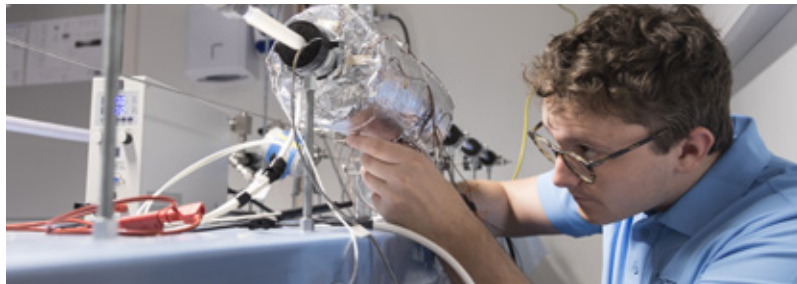


For the first time, in 2017, a major European Research Infrastructure Project (ERIC), a European legal entity, was awarded to a country from outside of the EU. Through ECCSEL ERIC, more than 50 laboratories in five European countries are coordinated from Trondheim. It was also the first ERIC to be set up in the Energy Sector. The opening ceremony took place in the presence of (from left): State Secretary Ingvil Smines Tybring-Gjedde, Norwegian Ministry of Petroleum and Energy, Sverre Quale Director ECCSEL ERIC and project director ECCSEL, Wolfgang Burtscher, Deputy Director-General of the European Commission's Directorate-General for Research & Innovation. The leader of the ECCSEL Svelvik CO₂ Field Lab Cathrine Ringstad, from SINTEF Industry explains to Mr. Burtscher, how CO₂ can be stored in waterfilled pores in sandstone reservoirs in the underground, illustrated with a sandstone core from the North Sea.

Infrastructure For All

A look inside the NTNU & SINTEF Thermal Engineering Labs. They are home to some of the ECCSEL ERIC infrastructure, available for use by industrial partners and research colleagues from across Europe.







WORLD-CLASS INFRASTRUCTURE

Headquarters of the ECCSEL ERIC network of laboratories and research equipment, including the Tiller CO₂ capture pilot plant



HANDS-ON EDUCATION

NTNU offers an International Masters in Natural Gas Technology, and hosts the Joint Nordic Masters in Innovative Sustainable Energy Engineering



A FORUM FOR DISCUSSION

Trondheim hosts several world-leading conferences in CCS and greenhouse gas technologies, attracting attendees from around the world



INDUSTRIAL RESEARCH

A major research and development centre for Equinor

TRONDHEIM



A European Capital of **Gas Technology**



Guest enjoying a lighter evening by the waterfront below the Equinor facility in Trondheim. Equinor hosted the conference dinner at GHGT-8 in 2006.

Bringing the world to Trondheim

A major role of GTS was to highlight the work going on at NTNU and SINTEF to an international audience. This was achieved in great part thanks to a series of events and conferences that brought people to Trondheim from all over the world.



More than 400 international researchers attended TCCS-10 in 2019.

Applying to host established conferences is one thing.
But to truly make an impact, the centre started two of its own events.

GHGT-8

The International Energy Agency (IEA) Greenhouse Gas Control Technologies (GHGT) conference series has established itself as the foremost conference bringing together the international community to discuss greenhouse gas control technology issues. GTS brought the 8th GHGT event to Trondheim in June 2006.

During the four-day event attended by almost 1,000 participants from 47 countries, hundreds of technical papers and posters were presented. It was the largest CCS conference to date. Representatives from NTNU, SINTEF and Equinor led many of the sessions, with speakers and panellists travelling from as far afield as the USA and Japan.

GTS continued to work with the IEA throughout the lifetime of the centre. In collaboration with BIGCCS, SUCCESS and UNIS, GTS arranged the IEA GHG CCS summer school on Norway's Arctic archipelago Svalbard in August 2010. The week-long programme brought together 56 young scientists from 32 countries along with 30 expert lecturers and mentors. Much of the programme focused on Norway's first experiment to investigate full-scale CO₂ storage technology in Adventdalen, a valley just outside the islands' main settlement Longyearbyen.

Trondheim CCS Conference (TCCS)

Since its inception in 2003, the bi-annual Trondheim CCS Conference Series has developed to be an essential meeting place for over 400 CCS experts from around the world. Today the event is organized by the Norwegian CCS Research Centre (NCCS). A typical event consists of hundreds of presentations and posters along with up to six parallel sessions.

Trondheim Gas Technology Conference (TGTC)

Along with the Trondheim CCS Conference, GTS also oversaw the establishment and hosting of the Trondheim Gas Technology Conference four times between 2009 and 2016. Keynotes typically focused on the industrial perspective, with detailed sessions on a wide variety of technical topics, from flow phenomena to conversion and separation technologies.



GHGT-8 reception at the Archbishops Palace next to the Nidaros Cathedral in Trondheim.



The boat trip to Steinvikholmen island was a memorable part of GHGT-8. Equinor served dinner on the beach while parts of the Olav Engelbrekson opera was performed from the stage.

GTS Far and Wide

In addition to the conferences hosted in Trondheim, GTS representatives travelled far and wide to report on the growing gas research activities taking place in the city. Here's a selection of the events that GTS representatives participated in:

- 2006:** Poland 2006 program, E-World Energy & Water in Essen
- 2008:** Scandinavian Renewable Energy Forum in Bergen, GHGT-9 in Washington DC
- 2011:** Gastech Amsterdam, LNG Tech Global Summit in Rotterdam
- 2012:** Barents Sea Conference, invited lecture at Arctic University of Norway in Tromsø

Building an Educational Platform with Equinor



Annual student visits with Equinor, brand new Master's programmes, fully-funded PhDs, and summer schools.



*NTNU Master students and GTS Director
Astrid Lilliestråle at Melkøya in 2013.
Photo: Klaus Henriksen, Equinor*

An important goal of GTS was to further the educational platform in Trondheim, in order to aid the recruitment of students and researchers who would lead the next generation of gas technology research. GTS played a major role in the development and launch of new international Master programmes at NTNU. The MSc in Natural Gas Technology and the MSc in Innovative Sustainable Energy Engineering launched in 2009.

Melkøya in the media

In 2013, the twelve Master students from NTNU selected to participate in a five-day excursion to the Melkøya natural gas processing and liquefaction plant in Hammerfest attracted the attention of local media. Student Mohamad Majzoub of Venezuela was interviewed by Finnmark Dagblad and spoke of his admiration that Equinor would welcome students into their plant for such an extended period of time.

The purpose of the trip was to give the students a comprehensive and practical understanding of how an LNG plant is operated. Emphasis was placed on describing working processes and how different disciplines work together. Students were challenged to use their expertise to understand operations in a modern production facility.

Valuable visits every year

GTS collaborated with Equinor throughout the life of the centre to organise annual trips to industrial plants. Other locations included the large, modern methanol plant at Tjeldbergodden and the Kårstø processing plant, the largest of its kind in Europe. Some of the participating students were offered Master's thesis work related to the plants.

Equinor's Cecilie Gotaas Johnsen said these kind of excursions are important for the students, GTS, the company, and the wider industry. "We are looking at positioning ourselves for the future, and in the future we will need new skills. The multidisciplinary breadth of skills in the students excellent, everything from petroleum engineering to cybernetics. The questions they ask on the trips give us new perspectives and we expose ourselves and the wider industry as potential employers to them."

NTNU's Hilde Venvik explains that the choice of students was deliberately broad: "Spending a week rather than a quick one-hour tour really gave the students a chance to see the theory in practice. But more than that, it gave them the opportunity to ask questions, develop opinions and go away with ideas for future projects. This is even more effective when the students bring unique perspectives from different disciplines."



PhD student spotlight

ASTRID LERVIK MEJDELL

PhD: Properties and application of 1-5 μm Pd/Ag23wt.% membranes for hydrogen separation

Supervisor: Prof. Hilde Venvik, Depart. of Chemical Engineering, NTNU

Astrid was one of several PhD students partly-funded by GTS that were looking at thin membranes for hydrogen separation. She predominantly worked at SINTEF's Oslo labs, where the membranes were developed. Today, she works as a Principal Researcher for Equinor.

What did your PhD involve?

It was a bustling environment with so many people – students, supervisors, professors – from different departments involved. There was a lot going on and this gave me new perspectives on other work areas. The GTS PhD students would meet annually, further developing our knowledge and networks.

How has energy research changed since then?

From my perspective it has changed radically. The global attention is on renewables and new energy opportunities, and you can see the change at Equinor too. The teams focused on renewables and low-carbon solutions have grown significantly.

What is your biggest memory from GTS?

As part of a joint NTNU-SINTEF delegation, I attended an international conference on membranes in Tokyo. It was so inspiring to step out of my focused area and understand the place my work had in an international context.

Equinor's involvement in GTS also played an important role in the centre being able to fund – fully and partly – so many PhD candidates. Some of them now work with Equinor.

GTS also played a role in the EnergiCampus Nord (ECN) initiative, a cooperation between NTNU and several universities and colleges across Norway with the aim of creating

a research-based educational programme within Energy Engineering in Hammerfest. Arne Bredesen and Eve Lien were involved.

In addition, GTS co-organised other events including the IEA GHG International CCS Summer School in 2010 on Svalbard.



*Melkøya.
Photo Helge Hansen, Equinor*



NTNU students discussing LNG loading and offloading with Equinor's Klaus Henriksen at Hammerfest LNG.



PhD student spotlight

LIYAN DENG

PhD: Development of Novel PVAm/PVA Blend FSC Membrane for CO₂ Capture.

Supervisor: Prof. May-Britt Hägg, Depart. of Chemical Engineering, NTNU

From 2005 to 2009, Liyuan studied for a PhD that was partly-funded by GTS.

Through the GTS platform, she took part in conference and a summer school, where she was able to present her work and network with other young researchers working in gas technologies. She continued her research with a postdoc and has remained at NTNU, where she now teaches and researches membrane separation technologies.

"Although I always knew I wanted to pursue a career in research, it was the experience during my PhD that set me on my current path within gas technologies. I began working with membranes for CO₂ capture and in doing so I was exposed to so much research on CO₂ emissions.

I take the battle against climate change very seriously and so have continued the GTS-funded research and worked with gas technologies ever since."

Competence Building



In 2018, the prize for young and outstanding researcher was awarded to Øivind Wilhelmsen, a Research Scientist in Gas Technology at SINTEF Energy Research, and Professor in Thermodynamics at the Department of Energy and Process Engineering at NTNU. Øivind has achieved a great deal very early in his career, and is an excellent representative of the unique collaborative relationship between NTNU and SINTEF. The prize was awarded to Øivind by Minister of Research and Higher Education Iselin Nybø, pictured.

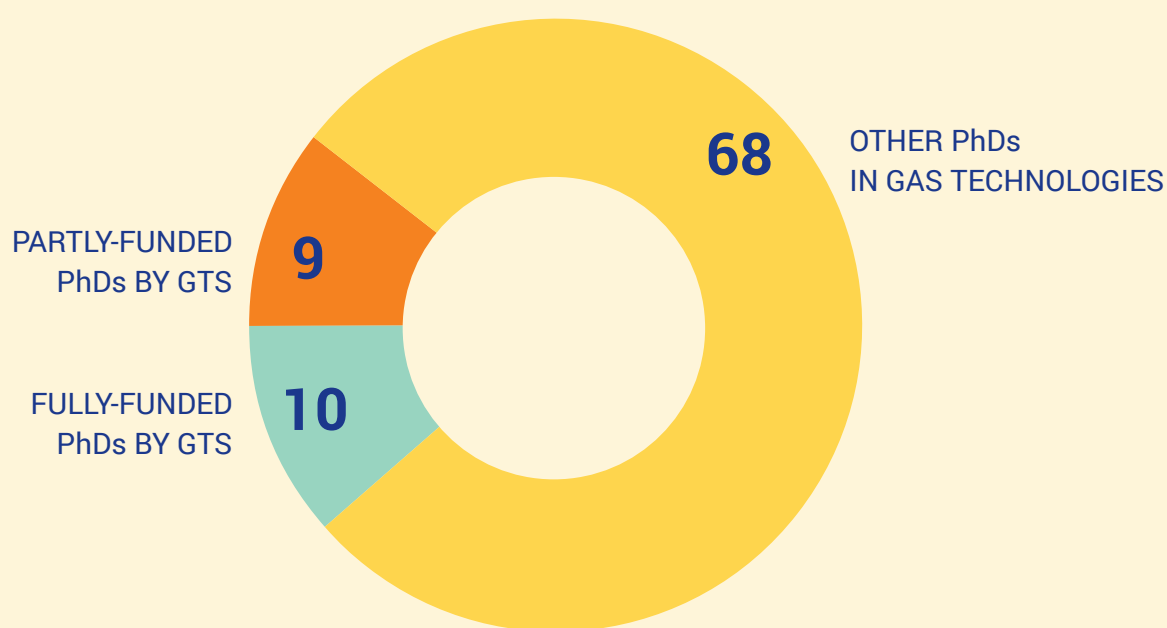
His most important contributions to research have been in the fields of equilibrium and non-equilibrium thermodynamics, a description of transport processes across planar and curved gas-liquid interfaces, a description of nucleation processes, the thermodynamics of CO₂ mixtures, and an understanding of thermodynamic stability in nanosystems.



IEAGHG's Summer School was hosted by NCCS in 2018 in Trondheim.

IEAGHG's Summer Schools is a CCS education program with international focus. With the location moving around the world, the program has now taken place in over 7 countries covering Europe, Australia, Asia and North America.

Equinor's involvement in GTS was instrumental in increasing the breadth of PhD candidates in gas technologies. Over the life of the centre, Equinor's financial commitment enabled nine fully-funded PhDs, along with many others that were partly-funded or that benefited from the joined-up platform that GTS helped to create in Trondheim.



PhDs fully and partly funded by GTS:

- Petar Aleksic** (2011): Experimental investigation of thermal effects in a hydrogen cryo-adsorption storage system.
Supervisor: Prof. Erling Næss, Dept. of Energy and Process Engineering, NTNU.
- Sissel Øksnevad Martinsen**: Climate Gas & VOC Emissions from Oil Cargo Tankers.
Supervisor: Professor Curtis Whitson, Dept. of Geoscience and Petroleum, NTNU.
- Ezequiel Manavela Chiapero** (2012): Two phase flow instabilities and flow maldistribution in parallel channels.
Supervisor: Prof. Maria Fernandino, Dept. of Energy and Process Engineering, NTNU.
- Magnus Jacobsen** (2011): Identifying active constraint regions for optimal operation of process plants:
With application to LNG and distillation processes.
Supervisor: Prof. Sigurd Skogestad, Department of Chemical Engineering, NTNU.
- Tom-Gøran Skog** (2014): Development of Hollow Fiber Membranes and Membrane Modules Sui for High Pressure Natural Gas Sweetening. Supervisor: Prof. May-Britt Hägg, Dept. of Chemical Engineering, NTNU.
- Andreas Helland Lillebø** (2014): Conversion of biomass derived synthesis gas into liquid fuels via the Fischer - Tropsch synthesis process: Effect of alkali and alkaline earth metal impurities and CO conversion levels on cobalt based catalysts.
Supervisor: Prof. Professor Anders Holmen, Professor Edd A. Blekkan, Dept. of Chemical Engineering, NTNU.
- Usman Shoukat** (2019): "Combined subsea hydrate control and H₂S removal"
Supervisor: Hanna Knuutila, Dept. of Chemical Engineering, NTNU.
- Il Woong Park** (2018): "Two-phase flow instabilities during flow boiling and control of wettability by micro-structured surfaces" Supervisor: Prof. Carlos A. Dorao, Dept. of Energy and Process engineering, NTNU.
- Eskil Aursand** (2019): Film boiling and rapid phase transition of liquefied natural gas.
Supervisor: Prof. Bernhard Müller, Dept. of Energy and Process Engineering, NTNU.
- Arjun Singh** (2008): Model-based predictive control of heat exchangers for production of liquefied natural gas (LNG).
Supervisor: Prof. Morten Hovd, Dept. of Chemical Engineering, NTNU.
- Zhengjie Zhu** (2009): The Least-Squares Spectral Element Method Solution of the Gas-Liquid Multi-fluid Model Coupled with the Population Balance Equation. Supervisor: Prof. Hugo A. Jakobsen. Dept. of Chemical Engineering, NTNU.
- David Grainger** (2007): Development of carbon membranes for hydrogen recovery.
Supervisor: Prof. May-Britt Hägg, Dept. of Chemical Engineering, NTNU.
- Inge Saanum** (2008): Experimental Studies of Hydrogen as a Fuel Additive in Internal Combustion Engines.
Supervisor: Prof. Johan E. Hustad, Department of Energy and Process Engineering, NTNU.
- Sverre Gullikstad Johnsen** (2007): An Analytical Mathematical Theoretical Study of Single-Well Push-Pull Echo Tests.
Supervisor: Prof. Curtis H. Whitson, Dept. of Geoscience and Petroleum, NTNU.
- Isabella Inzoli** (2008): Coupled transports of heat and mass at the surface of and inside silicalite.
Supervisor: Professor Signe Kjelstrup. Dept. of Chemistry, NTNU.
- Astrid Lervik Mejdell** (2009): Properties and application of 1-5 µm Pd/Ag₂₃wt.% membranes for hydrogen separation.
Supervisor: Prof. Hilde Johnsen Venvik, Dept. of Chemical Engineering, NTNU.
- Liyuan Deng** (2009): Development of Novel PVAm/PVA Blend FSC Membrane for CO₂ Capture.
Supervisor: Prof. May-Britt Hägg, Dept. Chemical Engineering, NTNU.
- Bjørn Lilleberg** (2011): On Mathematical Modeling and Numerical Simulation of Chemical Kinetics in Turbulent Lean Premixed Combustion. Supervisor: Prof. Ivar S. Ertesvåg, Dept. of Energy and Process Engineering, NTNU.
- Luis Castillo** (2013): An integrated framework for decision making on liquefied natural gas (LNG) projects.
Supervisor: Prof. Carlos A. Dorao, Dept. of Energy and Process Engineering.

Boards and Management

2003

The formal agreement between NTNU and SINTEF for the centre was signed on 27 January 2004. It had an initial duration of five years, with an evaluation planned after three years. Professor Bjarne A. Foss, NTNU and Per-Erling Frivik, SINTEF led the planning work prior to this.

2004

Board of Directors

Board Director: CEO Sverre Aam, SINTEF Oil and Energy
Bredesen, Arne M., Vice-Dean, NTNU – Faculty of Engineering and Technology, Head of NTNU Energy and Environment
Nicholson, David, Dean, NTNU – Faculty of Natural Sciences and Technology
Stori, Aage, Vice President Research, SINTEF Materials and Chemistry
Theodorsen, Ingve, Direktør, Statoil R&D

Management:

Dr. Foss, Bjarne A., Professor, NTNU
Frivik, Per-Erling, CEO Gassteknologi, SINTEF
Dr. Røkke, Nils A., Senior Research Scientist, SINTEF

2005

Board of Directors

Board Director: CEO Sverre Aam, SINTEF Oil and Energy
Bredesen, Arne M., Professor, NTNU Faculty of Engineering and Technology, Head of Energy and Petroleum, Resources and Environment
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering
Stori, Aage, Vice President Research, SINTEF Materials and Chemistry
Theodorsen, Ingve, Direktør, Statoil FoU

Management:

Dr. Foss, Bjarne A., Professor, NTNU
Dr. Røkke, Nils A., Senior Research Scientist, SINTEF

2006

Board of Directors

Board Director: President Sverre Aam, SINTEF Energy Research
Bredesen, Arne M., Director Strategic Area, Energy and Petroleum – Resources and Environment
Hägg, May-Britt, Professor, Department of Chemical Engineering, NTNU
Stori, Aage, Vice President Research, SINTEF Materials and Chemistry
Utengen, Svenn Ferry, Director, Statoil R&D

Management:

Dr. Foss, Bjarne A., Professor, NTNU
Dr. Røkke, Nils A., Senior Research Scientist, SINTEF

2007

Board of Directors

Board Director: President Sverre Aam, SINTEF Energy Research
Bredesen, Arne M. , Prof., Director Strategic Area, Energy and Petroleum – Resources and Environment
Ferry Utengen, Svinn, Director, Statoil R&D
Hägg, May-Britt, Professor, Department of Chemical Engineering, NTNU
Stori, Aage, Vice President, SINTEF Materials and Chemistry

Management:

Dr. Foss, Bjarne A., Professor, NTNU
Dr. Røkke, Nils A., Senior Research Scientist, SINTEF

2008

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Chairman: President Sverre Aam, SINTEF Energy Research
Bredesen, Arne M., Prof., Director of the Strategic Area, Energy and Petroleum – Resources and Environment
Hägg, May-Britt, Professor, Department of Chemical Engineering, NTNU
Wærness, Ole, Research Director, SINTEF Materials and Chemistry
Aasland, Siv, Director, Statoil R&D

Management:

Dr. Maria Barrio replaces Nils Røkke from January 2009
Dr. Bolland, Olav, Professor, Department of Energy and Process Engineering, NTNU
Dr. Røkke, Nils A., Vice President CCT, SINTEF

2009

Board of Directors

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Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering
Wærnes, Ole, Research Director, SINTEF Materials and Chemistry
Aasland, Siv, Director, Statoil R&D

Management

Dr. Barrio, Maria, Vice-President, Gas Technology, SINTEF
Dr. Venvik, Hilde J., Professor, Department of Chemical Engineering, NTNU

2010

Board of Directors

Chairman: Director Sverre Aam, SINTEF Energy Research
Bredesen, Arne M., Professor, NTNU Director of the Strategic Area, Energy and Petroleum Resources and Environment
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering
Rønnekleiv, Morten, Department Manager Gas Conversion, Statoil
Wærnes, Ole, Research Director, SINTEF Materials and Chemistry

Management

Dr. Barrio, Maria, Vice-President ,Gas Technology, SINTEF
Dr. Venvik, Hilde J., Professor, NTNU

2011

Board of Directors

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Bredesen, Arne M., Professor, NTNU Director of the Strategic Area, Energy and Petroleum Resources and Environment
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering
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Wærnes, Ole, Research Director, SINTEF Materials and Chemistry

Management

Dr. Barrio, Maria, Vice-President ,Gas Technology, SINTEF
Dr. Venvik, Hilde J., Department of Chemical Engineering, NTNU

2012

Board of Directors

Chairman: Director Sverre Aam, SINTEF Energy Research
Rønnekleiv, Morten, Department Manager Gas Conversion, Statoil
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Bredesen, Arne M., Professor, NTNU Director of the Strategic Area, Energy and Petroleum Resources and Environment
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering

Management

Dr. Barrio, Maria, Vice-President ,Gas Technology, SINTEF
Dr. Venvik, Hilde J., Department of Chemical Engineering, NTNU

2013

Board of Directors

Chairman: Sverre Aam, Director SINTEF Energy Research
Akporiaye, Duncan, Vice President Research, SINTEF Materials and Chemistry
Bredesen, Arne M., Professor, NTNU Department of Energy and Process Engineering
Johnsen, Cecilie Gotaas, Leader Sour and Acid Gas, Statoil
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering

Management

Lilliestråle, Astrid, Research Manager, SINTEF
Dr. Venvik, Hilde J., Professor, supplemented by Professor Magnus Rønning from October 2013, NTNU

2014

Board of Directors

Chairman: Sverre Aam, Director SINTEF Energy Research
Akporiaye, Duncan, Vice President Research, SINTEF Materials and Chemistry
Bredesen, Arne M., Professor, NTNU Department of Energy and Process Engineering
Johnsen, Cecilie Gotaas, Leader Sour and Acid Gas, Statoil
Hägg, May-Britt, Professor, NTNU Department of Chemical Engineering

Management

Johansen, Jon M., Business Developer, SINTEF
Dr. Venvik, Hilde J., Professor, Department of Chemical Engineering, NTNU

2015

Board of Directors

Chairman: Ingvald Strømme, Dean of the Faculty of Engineering Science and Technology, NTNU
Akporiaye, Duncan, Vice President Research, SINTEF Materials and Chemistry
Blekkan, Edd A., Head of department, Dep. of Chemical Engineering, NTNU
Johnsen, Cecilie G., Leader Sour and Acid Gas, Statoil
Mølnevik, Mona J., Research Director, SINTEF Energy Research

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Johansen, Jon M., Business Developer, SINTEF

2016

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Johnsen, Cecilie G., Leader Sour and Acid Gas, Statoil
Mølnevik, Mona J., Research Director, SINTEF Energy Research

Management

Dr. Fernandino, Maria, Professor, Department of Energy and Process Engineering, NTNU
Johansen, Jon M., Business Developer, SINTEF

2017

Board of Directors

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