FINAL Report

BIGCO2 R&D Platform

Phase II
2007-2011

BIGCO2

Host institution: SINTEF Energy Research

Contents

Attachments

1. Message from Chairman of the Steering Committee

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. It was named in Norwegian "Bruker Interesse Gruppe prosjekt CO_2" (English: User Interest Group project within CO_2). Thus BIGCO2 became the acronym and after thinking about it, we realized that BIG is beautiful. For SINTEF it was a major consolidation of the CCS R&D work being conducted in it's various institutes, it integrated capture, transport and storage. This decision was taken by the top management in SINTEF and it proved to be a wise move. There are synergies to be collected from researchers working together in a large project even if the field of work is so different as storage and capture of CO_2. The success of this has been demonstrated in numerous EU projects that have been initiated through BIGCO2, and now the most natural thing on earth is value chain considerations for CCS.

BIGCO2 Steering Committee, Chairman
Nils A. Røkke
(Photo: Geir Otto Johansen)

It has been a real pleasure to guide BIGCO2 in the various phases of development and see the results of the project. New knowledge has been produced in seismic monitoring of CO_2, membranes and sorbent, enabling further development into commercial products and spin-offs in solvent development.

A final reflection is that it took courage from all parties at the time that BIGCO2 was established to actually do it. It restructured the CCS R&D strategy in SINTEF, it took courage from the industrial parties to engage in such a large project with sizeable contributions, and it took a lot of courage from the Research Council of Norway to invest this kind of money into one project. I think the results speak for themselves, BIG has now become a brand for excellent CCS R&D performed in Norway - be it BIGCO2, BIGCCS, BIGH2 or BIGCLC.

See you in the next BIG project!

2. Message from the BIGCO2 Coordinator

Dear BIGCO2 partners and friends!

Thank you for having contributed to the development of the international CCS deployment through being a partner in BIGCO2 for years. The journey we have made together has resulted in important results for the industry and society. With BIGCO2 we learned to join forces in CCS research and inspired others to do the same. CCS includes several research topics; hence industrial solutions require the multidisciplinary approach that BIGCO2 has represented.

The results from BIGCO2 have been shared between the partners, through publications, and indirectly through additional research activities and studies. Finally, the results have been used when establishing spin-off activities with industrial partners already in BIGCO2 or others.

Totally, BIGCO2 has produced 123 publications. BIGCO2 was represented with five oral presentations and seven posters at GHGT-10 in Amsterdam 2010.

The IEA Energy technology perspective 2012 states that to meet the "two degree scenario", carbon capture is essential. Without CCS the additional investment in electricity will increase with 40 percent. Further, CCS is the only technology on the horizon today that would allow industrial sectors to meet deep emissions reduction goals.

Let this encourage us to continue our efforts in CCS deployment!

BIGCO2 Centre Coordinator
Mona J. Mølnvik
(Photo: Gry Kari Stimo)

3. Message from the Research Council of Norway

CCS was at an early stage put high on the political agenda in Norway. CO_2 injection was initiated at Sleipner already in 1996 as a result of the CO_2 tax implementation by the Norwegian government in 1992. The "Klimatek" program was established in 1997 with focus on several CO_2 reduction activities and later in 2002 the first competence projects on CO_2 capture started, which was the precursor for the BIGCO2 project.

In the following years there was an increased political and public debate on climate change and how to mitigate CO_2 emissions. The message was no new gas power plants without CO_2 capture and storage and it was urgent to build up competence in this area rapidly and effectively. In 2005 SINTEF together with research partners NTNU, University of Oslo and CICERO managed to set up an industrial consortium and establish a broad program on power cycles with CO_2 capture and storage and CO_2 for enhanced oil recovery (EOR). There were, and still are, no prioritized capture technology routes and a competence program bringing up several technologies were deemed important. SINTEF was able to gather experts from various research areas such as combustion, process engineering, process chemistry, and materials as well as reservoir scientists and engineers. This represented a solid scientific basis that has been able to create new and important results continuously since the start in 2005. Just as important is education of PhD and Post Docs and the expansion of the program consortium to include new international partners.

A broad-based national political climate agreement in 2008 reached by the Norwegian Parliament (Stortinget) made the basis for the Research Councils establishment of the new centers on environmentally friendly energy research (CEER). BIGCO2 was important for the successful establishment of the Research Centre BIGCCS including a continued broad scope on capture, transport, storage and the whole CO_2 value chain analysis. BIGCO2 have also paved way for development of Aker's capture technology program SOLVit. Furthermore, BIGCO2 has contributed significantly to boost the knowledge and quality within CCS and bring Norway in a leading position within CCS development.

BIGCO2 was also the basis for several EU FP7 projects and has contributed to the quality of the applications within CCS. Norwegian applications within CCS have a remarkable high success rate within FP7 where almost 45% of the applications have resulted in EU FP7 projects.

Overall BIGCO2 has been a very important contributor both nationally and internationally to boost the knowledge and quality of research and development related to CCS.

Åse Slagtern
Research Council of Norway
(Photo: The Research Council of Norway)

The Research Council of Norway

4. Summary and conclusions

The *BIGCO2 R&D Platform* (BIGCO2) has investigated several technological options for CCS, and developed the scientific basis for future CCS solutions with lower cost and higher efficiency than current solutions taking environmental aspects into account. All main routes for CO_2 capture have been investigated. BIGCO2 represents a coordinated effort to establish the scientific platform for developing new knowledge and technology for power production with CO_2 capture and storage. So far the project and its predecessors have resulted in progress within multiple research areas related to CCS and have led to a significant number of spin-off projects.

The BIGCO2 aim has been to develop knowledge to enable power generation with CCS. Tangible goals were: 90 % CO_2 capture rate, 50% cost reduction, and a fuel-to-electricity penalty less than 7 % compared to state-of-the-art power generation.

Partners of the Consortium have been: Statoil, GE Global Research, Statkraft, Aker Clean Carbon, Shell, TOTAL, ConocoPhillips, ALSTOM, DLR, TUM, NTNU, CICERO, SINTEF Materials and Chemistry, SINTEF Petroleum Research, and SINTEF Energy Research. The University of Oslo has been a subcontractor to the project. BIGCO2 has benefited from a strong collaboration with the combustion research facility at Sandia National Laboratories (USA). The main sponsors of BIGCO2 are the *Research Council of Norway* and *Gassnova*, with considerable co-funding from industry partners.

Over the period 2007-2011, The BIGCO2 has developed knowledge and technology supporting demonstration activities of power generation with carbon capture and storage at industrial scale. The Consortium has administered a budget of 16 M€. The main outcomes of the project are:

- New knowledge and technology that has advanced the CCS technology considerably closer to the demonstration stage
- New R&D infrastructure facilitating vital experimental activities has been acquired between the R&D partners
- A new generation of highly skilled researchers (PhDs and post.docs) has been educated Candidates have already been recruited by the industrial partners
- A network has been established consisting of industrial and R&D entities
- Established several important spin-off projects, among others the International CCS Research Centre (BIGCCS)
- BIGCO2 has been a steppingstone for establishment of several innovation projects including *SolvIt, CO2field lab, and BIGH2*

Some of the main findings/achievements under the different tasks are listed below:

High temperature membranes for clean power production (A)

- Development of cost efficient and environmentally friendly membrane fabrication procedures
- Demonstration of asymmetric membranes with dense layers down to ~10 µm thickness
- Close to targeted flux value of ~10 $mL \cdot cm^{-2} \cdot min^{-1}$ was obtained at ambient pressure, and is within reach for optimized membranes under realistic operating conditions
- First demonstration of high pressure membrane testing reported in Norway
- Tailored glass ceramic seal systems are more promising with respect to compatibility with membrane materials

Improved post-combustion capture by solvents development, systems modeling, simulations (B)

- A new absorbent class is developed – amine amino acid salts.
- A new solvation model is developed - Explicit Solvation Shell model (ESS)
- A new method is developed for measuring the protonation reaction enthalpy
- Consistent thermodynamic models for CO_2/amine/water systems are implemented and verified using experimental data
- A dynamic model enabling prediction of plant behavior at transient conditions is developed
- CO2SIM has been developed as an in-house simulation tool

Pressurized combustion of enriched fuels (C)

- The findings constitute a solid foundation for development of combustion systems for CCS applications, up-scaling to high pressure, and pilot size projects
- Fundamental studies on oxy-fuel combustion resulted in a library of data for laminar flame speeds and ignition delay times

- Experiments showing that heat flux from oxy-fuel flames at high O_2 concentrations can be three times higher than in air flames
- Measured in-flame oxy-fuel combustion concentration and temperature data are collected for validation of computational simulation
- Limitations of oxy-fuel combustion for gas turbine application are: the requirement to use as little oxygen excess as possible; and keeping high flame stability at the burner while containing the flame temperature within the material limit
- A remarkable result in hydrogen combustion is the discovery of the region of reversing flow in front of the flame during propagation of the flame along the wall
- The temperature and pressure dependency are established for important chemical reactions, which will give more accurate results from hydrogen combustion modeling
- A high fidelity mixing model is developed and implemented in CFD simulations

Power cycle integration and analysis including unit modeling and simulation (D)

- Steady-state part-load analysis and knowledge about the fast dynamics of NGCC operation show that the NGCC will always be capable of supplying the capture unit with sufficient amounts of steam
- If complete fuel conversion is not feasible for CLC reactors, process designs allowing recycling of recovered but less pure fuel streams should be considered

CO_2 chain analysis (E)

- Development of a methodology for techno-economic assessment of CO_2 chains and implementation of a calculation tool for techno-economic analysis – EXPAND
- The methodology and tool were used to create and execute case studies in such a way to help understand the governing trends and dependencies within a CCS chain and between the CCS chain and its environment
- Case studies are preformed, illustrating the impact of technology improvements targeted on the economy of the whole chain, and case studies on CO_2 transport infrastructure focusing on optimization of pipeline network, effects of ownership, and political incentives
- The methodology and tool enable comparison and selection of promising options for CCS chains by evaluating techno-economic criteria
- The methodology has the potential to help to design efficient incentives and measures to stimulate invention, innovation, and realization of CCS

Enhanced oil recovery and safe underground storage of CO_2 in geological formations (F)

- A formulation for description of the stability of the boundary layer at the interface between the CO_2 gas cap and the underlying aquifer water column is developed. The formulation allows better predictions of how long it takes before convection currents forms, and will lead to improved predictions of storage safety
- Models are developed for investigation of leakage mechanisms
- A simple mass-conservation-based model is developed for investigation of scenarios involving a global ensemble of storage sites. This model was further developed to encompass both the Norwegian and UK sectors of the North Sea
- A Full Waveform inversion method is improved to be able to work with data sets such as the ones from Sleipner

Chemical looping combustion (G)

- Oxygen carrier materials are developed based on in-expensive industrial tailings, by-products and naturally occurring minerals and ores. A large number of sources are surveyed. A manganese ore was selected as the most promising for CLC purposes
- Three different methods for fabrication of oxygen carriers suitable for CLC have been tested and evaluated: spray granulation, spray drying, freeze granulation
- A new design is proposed a 150 kW CLC reactor system, with two interconnected circulating fluidized bed reactors
- A lab-scale rotating bed reactor for chemical looping combustion was constructed and tested using a CuO/Al_2O_3 oxygen carrier and methane as fuel. Around 90% CH_4 conversion and >90% CO_2 capture efficiency based on converted methane has been obtained
- Significant increase in knowledge and experience to the BIGCO2 partners about CLC processes, reactor systems and oxygen carrier materials

5. About BIGCO2

This chapter gives a summary of the vision and objectives of the project, the research approach, the organization, the consortium, and funding.

5.1 Visions and goals

The project has assembled the critical mass of expertise to suggest feasible solutions within a framework of technical, environmental and economic viability. This endeavor corresponds to the issue of security of energy supply – as it may allow Norway to make use of its vast indigenous fossil reserves with the lowest practical greenhouse gas emissions.

The project aspired to complement and extend knowledge from existing and on-going national and international capture and storage programs that its partners were (or have become) involved in. Hence, the high level of proficiency linked with the complementary skills and expertise mobilized in this KPN project has ensured that the project remained at the forefront of international CCS research.

The following objectives were stated at the beginning of the project period:

Tangible objective: To pave the ground for gas power generation that employ CO_2 capture and storage with the potential of fulfilling the following compound target:

- 90% CO_2 capture rate
- 50% cost reduction
- fuel-to-electricity penalty less than seven percentage points compared with state-of-the-art gas power generation

Scientific objective: To generate and refine knowledge and topical comprehension of power cycle integration via systems engineering (synthesis), capture technologies (combustion, flue gas scrubbing, and membranes) and storage. Important aspects have been the characteristics of the inherent potential, constraints and the governing mechanisms pertaining to solutions that facilitate capture and storage of CO_2. The fulfillment of this objective has relied on targeted fundamental and applied research, governance, and international involvement.

Technological objective: To shorten the lead-time and improve certainty of plant characteristics and limit the technical and commercial risk at an acceptable level, which jointly could lead up to a decision of setting up a green-field gas power plant in Norway in compliance with the stated tangible objective.

5.2 Research approach

When establishing capture strategies one should keep in mind that options are rather complex and plentiful. Consequently, this project has covered several fields of expertise. The fulfillment of the objective of BIGCO2 has relied on targeted fundamental and applied research, governance, and international involvement.

A methodology to rank concepts on a common basis has been applied including cost assessment, and validation of critical elements. This endeavor has included assessment of (novel) emerging concepts that were deemed capable of fulfilling the stated target. A trade-off was established in order to balance the target should the capture rate, the cost reduction or the fuel penalty for any reason deviate from the pre-defined level. This was also to reflect the maturity level according to a coarse designation: a) off the shelf, b) straight-forward to design, c) extensive technology development, and d) requiring a technology breakthrough. Technology breakthroughs are much dependent on the progress in related sciences – especially materials, chemistry and thermodynamics – and appropriate assessment and ranking of candidate technologies has included assumptions on time frame for commercialization within 5 years (short-term), 5-10 years (medium term), and beyond 10 year (long term).

Prospective concepts that were identified for further scrutiny under the project were:

1. Pre-combustion reforming cycles for natural gas (IRCC) – with provision for hydrogen and hydrogen enriched fuels for air-breathing gas turbines;

2. Hydrogen and oxy-fuel combustors for gas turbines including advanced power cycles using oxygen transport membranes focusing on material performance, stability and operational aspects;

3. Chemical looping combustion for oxygen supply, primarily to be considered with reforming cycles and oxy-fuel combustion (a separate project, BIGCLC, was granted by the RCN in spring 2006).

4. Post combustion focusing on absorbents and adsorbents including their environmental impacts.

5.3 Organization

The project was operated with a rather flat structure. Each *task leader* has reported directly to the ***project management team*** (PMT) and has been responsible for the work packages within the task. The ***project coordinator*** has reported regularly and upon request to the steering committee.

The project ***steering committee*** has approved the annual implementation plans and has been responsible for budgetary allocations to the project. In case of conflicting interests the steering committee has had the decisive power. Including its ***chairman***, the steering committee has comprised one representative from:

- SINTEF Energy Research
- SINTEF Petroleum Research
- SINTEF Materials and Chemistry
- The Gas Technology Centre NTNU-SINTEF
- NTNU
- Each fully contributing industrial partner

The project steering committee met at least twice per year, whereas, extra-ordinary meetings could be convoked by any member of the project steering committee.

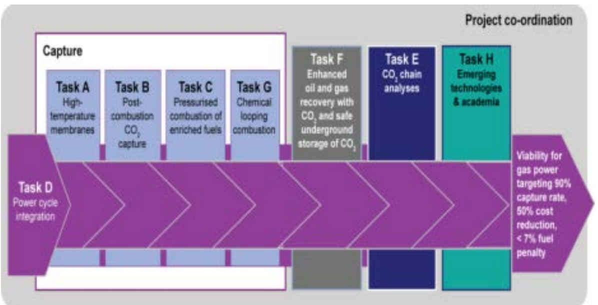
SINTEF Energy Research appointed the chairman of the project steering committee. Voting was done be by simple majority in all decisions except for critical decisions that required 2/3 majority. The term ‘critical decision’ refers to any case that could lead to either of the following events; discontinuity of some activity(ies), redistribution of budget and/or change in the partnership.

The *PMT* has included the project coordinator and the support team (administrative, legal and financial) that was responsible for the day-to-day operations, and for reporting to the project steering committee via coordinator. The project management team has managed the project and been operationally responsible for the progress and performance of the consortium, as well as the technical achievements of the project and the quality thereof.

The PMT has met more or less monthly with the task leaders to provide regular updates regarding status and progress. These meetings have also served as a scientific forum for cross-linking the project. The PMT has been responsible for all project-related coordination with the Research Council of Norway, and otherwise initiated specific dissemination actions. Furthermore, the PMT has been instrumental in organizing the ***consortium day***, and constituted the scientific committee according to the following functions:

- Consortium day - a meeting place for the stakeholders to provide guidance.
- Scientific committee - an ad-hoc advisory function that has drawn upon internal or external experts.

The organization of the research activities are shown in the figure below.



BIGCO2 research tasks

5.4 The consortium

Major stakeholders of the project have been:

- <u>R&D providers:</u> SINTEF Energy Research, SINTEF Materials and Chemistry, SINTEF Petroleum Research, the Norwegian University of Science and Technology, University of Oslo

(Norway), CICERO (Norway), Deutsches Zentrum für Luft- und Raumfahrt e.V (Germany) and the Technical University of Munich (Germany).

- Energy providers: Statoil (Norway), Shell Technology Norway, Total E&P Norway, ConocoPhillips (Norway), and Statkraft (Norway).
- Technology providers: Alstom (Switzerland), GE Global Research (Germany), Aker Clean Carbon (Norway).

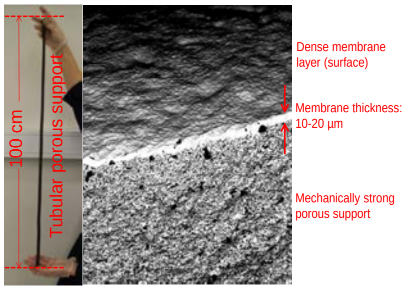
5.5 Funding

The overall budget for the BIGCO2 project has been NOK 130 million over the period 2005-2011, which includes two phases. The budget for Phase II (2007-2011) has been NOK 106 million. The Research Council of Norway and Gassnova SF have contributed 75% of the total funding, and the partners have contributed the rest.

6. Results from research activities

6.1 High temperature membranes for clean power production (Task A)

The membrane activities in BIGCO2 have given significant drive to the national research activities on ceramic ion conductors for high temperature gas separation with the involvement of three major actors in the field; NTNU, UiO and SINTEF. The main focus has been on ***oxygen transport membranes*** (OTM) offering extraction of pure oxygen from air at high temperature, in principle with 100% selectivity. The integration of such membranes in high temperature processes, i.e. for oxy-fuel combustion, has obvious advantages as compared to traditional cryogenic distillation. There are still scientific challenges to tackle before such technology will be commercially viable, in particular when it comes to up-scaling of membrane and module fabrication procedures. SINTEF has demonstrated development of cost efficient and environmentally friendly membrane fabrication procedures. Starting with preparation of disk-shaped membranes of 10-20 mm diameter, a gradual up-scaling has resulted in tubular porous supports up to 1 m length (figure a) produced by ceramic extrusion. The technique in itself is already used for commercial production of tubular ceramics. Water based extrusion pastes developed by SINTEF provides inexpensive alternatives to existing procedures where porosity and pore size distribution is tailored by addition of environmental friendly combustible pore formers. As the membrane thickness is crucial for significant oxygen flux, thin dense membrane layers are deposited onto the mechanically strong porous supports giving asymmetric membrane geometry. Routes for preparation of stable suspensions, required for coating of dense membrane layers, are developed and automated dip-/spray-coating techniques (commercial used for large scale coatings) used for deposition of dense selective layers onto the supports. By this approach SINTEF has demonstrated asymmetric membranes with dense layers (figure b) down to ~10 µm thickness which, according to preliminary flux models for studied material system, is sufficient to obtained targeted flux value of ~10 mL·cm^{-2}·min^{-1}.



a) b)

Extruded tubular porous support. b) SEM micrograph (cross section view) of asymmetric membrane). (Photo: SINTEF)

In order to assemble the produced membranes into larger modules, sealing technology is a key issue. In addition to the tailoring of glass ceramic seals compatible with the selected membrane material systems, brazing procedures have been investigated and tested for single tube membrane modules. Silver based braze was successfully applied for assembly and testing of single tube membrane module, however, the module failed after 3 weeks due to reaction between the braze and steel base. Conclusions from in-debt studies of tailored glass ceramic seal systems indicate that these are more promising with respect to the compatibility with the membrane materials. The next step will be to determine long term stability under realistic operating conditions. Joint couple compatibility studies of glass ceramic seals (combined with membrane material/steel base) are more promising, however, results from long term and pressurized testing of complete modules using these seals are still missing.

Based on the current development of OTM technology it is difficult to predict the cost of large scale membrane modules and this has not yet been evaluated within BIGCO2. Conclusive results for membrane life time cannot yet be obtained, however, high temperature flux measurements have been conducted over a period of more than 4000 hours. From measurements under atmospheric conditions oxygen flux of 4 mL·cm-2·min-1 was obtained for asymmetric membranes (10 µm thick dense layer on porous support) at 1000°C. The first pressurized measurements at elevated temperatures reported in Norway were performed with applied oxygen partial pressures in the range of 0.2 – 6.4 bars, realistic conditions for commercial applications. As these results were not performed with optimized asymmetric membrane (thin dense layer) the reported fluxes are <1 mL·cm-2·min-1, however, the flux dependency of the oxygen partial pressure difference (pO2feed - pO2permeate) is determined. These results will be crucial for developing a more accurate flux model that can determine under which conditions the targeted flux of > 10 mL·cm-2·min-1 can be reached. Preliminary conclusions indicate that this target is within reach for the developed asymmetric membranes in realistic operating temperatures and pressures. This, along with further investigation of improved membrane properties will now be pursued in BIGCCS Task 1.2, which so far has focused on hydrogen transport membranes.

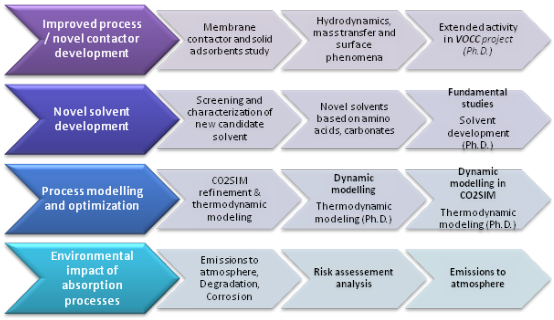
In addition to the initiation of membrane activities within the BIGCCS Centre, BIGCO2 has facilitated national publicity around OTM technology (i.e. through popular scientific publication) and increased Norwegian involvement in international projects like DECARBit and HETMOC (EU FP7), where further steps towards commercialization in form of pilot activities are now planned.

BIGCO2 has educated one PhD (NTNU) specifically on glass ceramic seals for high temperature membranes. Another PhD (UiO) graduating in 2012 is investigating new materials for hydrogen transport membranes which will be pursued within the BIGCCS Centre. Additionally, a post doc at NTNU is completing the work on membrane fabrication/material properties in 2012.

6.2 Improved post-combustion capture by solvents development, system modeling and simulation (Task B)

What we have found and discovered:

- A new absorbent class was developed – amine amino acid salts. Pilot plant tests showed that they may be good candidates enabling to reduce the energy requirement in CO_2 capture process with minimal environmental impact. The main challenge with such systems may be solvent degradation. In the amino acid amine systems we have tested so far degradation has been significant.



- Temperature dependency of carbamate stability constants and protonation constants for different amines was studied experimentally and by molecular modeling.
- A new solvation model was developed - ESS (Explicit Solvation Shell model), this can be utilized to predict key equilibrium constants for CO_2 absorption.
- A new method was successfully developed for measuring the protonation reaction enthalpy.
- Two consistent thermodynamic models (eNRTL, UNIQUAC) for CO_2/amine/water systems were implemented and verified using experimental data.
- Dynamic model enabling to predict plant behavior at transient conditions was implemented and verified against pilot plant data (VOCC)
- CO2SIM has been developed as an in-house simulation tool developed through several projects and used in several projects. All work done in BIGCO2 for CO2SIM was based on MEA solution. The code may be made available to organizations with interest in application.

What practical implications this has:

- New solvent system suggested for CO_2 absorption process
- Knowledge gained on two main equilibrium constants in amine systems
- Importance of the dynamic modeling was shown and model developed

- Simulations on proprietary solvent or any other solvent of interest may be done in CO2SIM.

New research topics – further work:

- Study of the amine amino acid salt systems for post-combustion CO_2 capture including screening of candidate solvents, solvent characterization, degradation, corrosion study and pilot test.
- Solvent degradation and emissions. This is a topic that has gained attention in the last few years and a lot of work has been done in various projects, particularly worked financed by Gassnova (CCM) and TCM.
- Thermodynamics in multicomponent systems. This is important for example for mixed amines systems where number of reactions and species in the system is significantly increased compared to the single solvent system.
- Process and solvent development. There has in recent years been significant activity on absorption based CO_2 capture. While a lot of improvements have been made, there is still likely to be substantial room to optimize the process further.

Publications – summary

- 16 peer-reviewed publications in following journals: *J. Chemical and Engineering Data, Industrial & Engineering Chemical Research; Chemical Engineering Science; Chemical Engineering and Processing*; *Int. J. of Greenhouse Gas Control; J. Chemical Thermodynamics.*
- 9 papers published in *Energy Procedia*
- 1 *patent application* - Svendsen, H.F., Mejdell, T., Hoff, K.A., Juliussen, O., Aronu, U.E. Absorbent system for carbon dioxide capture. WO 2010/053377 A1.
- More than 10 *conference presentations*

Education –summary

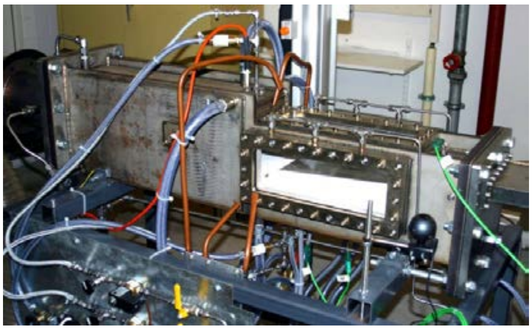
One post-doc and two PhD were fully supported and two PhD were partially supported by BIGCO2 in Task B. In addition several summer students and master students were involved in the research work at different stages of the project.

6.3 Pressurized combustion of enriched fuels (Task C)

Using hydrogen as a fuel or pure oxygen instead of air in a combustion chamber are two possible methods to facilitate the capture of CO_2 from power plants. Task C of BIGCO2 has been dedicated to solving the challenges related to the conception of burners that can operate with hydrogen or oxygen.

Oxy-fuel power generation is a new technology customized for CCS. As a result, the fundamental aspects of combustion in oxy-fuel atmosphere need to be reviewed, updated and documented. To fill this knowledge gap, Task C has studied generic experimental flame configurations with a systematic comparison with the corresponding air supported combustion cases. Fundamental studies on oxy-fuel combustion have resulted in a library of data for laminar flame speeds and ignition delay times which are necessary for burner design.

Experiments on laboratory scale flames using state-of-the-art measurement techniques revealed that the heat flux from oxy-fuel flames at high O_2 concentrations can be three times higher than from air flames, but the local soot formation is much less important. This has important implication in the design of combustion chambers which must be adapted to recover the combustion heat. In addition, species and temperature data measured inside the flame has provided validation data for testing computational simulations. Finally, oxy-fuel combustion tests in realistic conditions have been performed at DLR at up to 5 bar, showing that stability could be achieved and that pre-heat temperature was an important parameter. All the studies performed on oxy-fuel combustion during the project duration have highlighted that the limitations of oxy-fuel combustion for gas turbine application are: the requirement to use as little oxygen excess as possible; and keeping high flame stability at the burner while containing the flame temperature within the material limit.



Test rig for studies of basic properties.
(Photo: TUM)

The pre-combustion capture relies on the use of a gas turbine fired with hydrogen as fuel. The implementation of Lean Premixed burner techniques to reduce the NOx emissions, is hindered by the easiness of hydrogen flames to dangerously propagate inside the burner. A remarkable knowledge gain has been brought by the experimental study at TUM, revealing region of reversing flow in front of the flame during propagation of the flame along the wall. The new understanding of this process and the measurement of safety-critical flashback limits are considerable improvement as compared to the widely adopted model for the design of combustion chamber. A high-level theoretical study in collaboration with SANDIA National Lab has provided the temperature and pressure dependence of important chemical reactions which will give more accurate results from computational modeling of hydrogen combustion. From a computational flow dynamics (CFD) perspective, two models have been developed. One is particularly well adapted to predict aerodynamic mixing in flows containing hydrogen and has potential to improve the accuracy of numerical simulations of hydrogen combustion. The second is a tool to predict combustion induced acoustic instabilities which can destructively occur in gas turbine combustors, and hence avoid them.

The findings and activities of Task C constitute a solid foundation for the development of combustion systems for CCS applications and a necessary step towards the conception of pilot size projects, as demonstrated by two newly established GASSNOVA projects. The research activity to pursue is to move towards the realization and implementation of CCS at a larger scale. In that perspective, the Task C of BIGCO2 has provided fundamental knowledge that forms the basis for up-scaling to high pressure and pilot size. In addition, the oxy-fuel activity must be expanded to other fuels: coal and heavy oils, and other technologies: oil extraction/recovery processes and Carbon Capture from industrial sources.

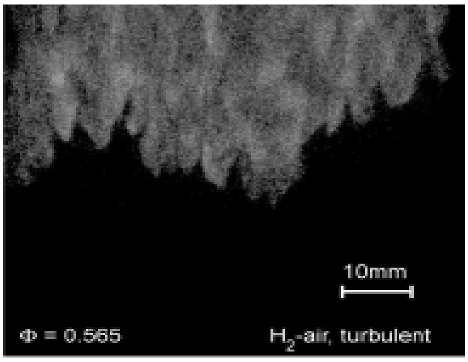


Image showing a flashback process.
(Photo: TUM)

Task C has generated 12 peer-reviewed publications (2 of which are still under revision) in the following journals: J. Physical Chemistry A; J. Engineering for Gas Turbines and Power; Proc. Combustion Institute; Experimental Thermal and Fluid Science; J. Sound and Vibration; Experiments in Fluids; Combustion and Flame; Flow, Turbulence and Combustion; and Energy Procedia. The work of Task C in BIGCO2 has been represented in the form of presentations in more than 10 conferences. In relation to Task C, there have been 3 PhD (2 at NTNU + 1 at TUM) and 2 post-doc and a total of 5 student internships. Two visiting researchers from Japan and France have been hosted in activities related to BIGCO2.

6.4 Power cycle integration and analyses including unit modeling and simulation (Task D)

The original objectives formulation for Task D aimed at evaluating the potential of novel CO_2 capture technologies with respect to technical and economic criteria and the targets of BIGCO2. Due to a wish to go more in-depth in the research, focus was increasingly directed to post-combustion capture. More precisely, solutions to integrate amine capture with the natural gas combined cycle (NGCC) were investigated in a systematic manner.

In the final journal paper from Task D, an investigation was made of two integration options of the NGCC with amine capture: one with a conventional triple-pressure heat recovery steam generator (HRSG) with steam extraction for solvent regeneration from the crossover between intermediate and low-pressure (IP/LP) steam turbines, and one configuration where 40% of the heat for solvent regeneration was taken from the low-temperature region of the HRSG, and the remaining 60% from the IP/LP crossover. The latter option showed nearly the same performance as the triple-pressure configuration both at full- and part-load, but with a 38% heat exchanger surface reduction, which should be economically beneficial. Also part-load operation of the two integration options was investigated. An important overall conclusion for both configurations, drawn from the steady-state part load analysis and knowledge about the fast dynamics of NGCC operation, is that the NGCC will always be capable of supplying the capture unit with sufficient amounts of steam to maintain 90% CO_2 capture. In the future the work on post combustion capture from NGCC will continue and some of the issues to investigate in an integrated manner for power plant and capture plant include:

- Investigate the overall NGCC efficiency gain for alternative solvents relative to MEA.
- Investigate other capture unit configurations, e.g. absorber intercooling, lean vapour recompression.
- Operation of the capture unit (dynamics, steady state, start-up, shut down) with variable capture rate scenarios.
- Investigation of operation and efficiency with exhaust gas recirculation to increase CO_2 concentration in absorber.

From simulations of chemical looping combustion (CLC) processes, the consequences of incomplete fuel conversion were investigated, for instance reduced process efficiency. Recovering un-burnt fuel components will complicate the overall process considerably and may be necessary for ensuring satisfactory process efficiency and high purity of captured CO_2. If complete fuel conversion is not feasible for CLC reactors, process designs allowing recycle of recovered but less pure fuel streams, examples of which have been proposed in Task D, should be considered.

Nine peer-reviewed articles in the following journals: International Journal of Greenhouse Gas Control, Journal of Solid State Electrochemistry, Energy and Fuels, Journal of Membrane Science, Energy & Environmental Science. An article will be submitted to International Journal of Greenhouse Gas Control in 2012. Five conference proceedings papers were given: Energy Procedia, DYCOPS 2010 Symposium, and 2nd Annual Gas Processing Symposium. 13 international conference presentations were produced.

One guest researcher from VTT in Finland worked in Task D for two months in 2009, contributing to one GHGT-10 presentation and proceedings paper.

One MSc and one PhD student have graduated. In addition, one PhD student is expected to graduate during 2013 after the closing of BIGCO2.

6.5 CO_2 chain analysis (Task E)

The CO_2 chain is affected by a rather complex set of variables: technology, economy, environmental aspects, political and regulatory issues as well as public acceptance. A systematic approach is required in order to analyze the effect of each particular variable and their cross-effects. *The main objectives of Task E were to provide a consistent and transparent methodology for analysis of CO_2 chains and to illustrate on relevant case studies the governing mechanisms within CCS and their dependencies on various parameters*.

We have developed a methodology for techno-economic assessment of CO_2 chains and implemented a calculation tool for techno-economic analysis - EXPAND. The methodology is based on standardized framework, transparent and consistent tools, carefully defined case studies, and qualified interpretations of results. The EXPAND tool is a calculation tool for Net Present Value (NPV) analysis – a pure economic analysis and performing incremental analysis – so that only the effects of CCS implementation are evaluated. However, the methodology and tool can only be used when the case studies are designed appropriately to answer specific questions. In the investigations within Task E, the methodology and tool were used to create and execute case studies in such a way to help understand the governing trends and dependencies within a CCS chain and between the CCS chain and its environment. EXPAND was designed to be consistent and transparent such that if reliable input data are available, reliable results will be attained which can be a great value to industry. The tool can also be used to give guidance and support as long as qualified guesses are used as input data in a comparative manner. This is also a helpful tool for communication between researchers working on the development of CCS technologies and for the general public.

Main results

Case studies were preformed, illustrating what would be the impact of the achieved technology improvements targeted within other tasks under BIGCO2 project on the economy of the whole chain, and case studies on CO_2 transport infrastructure focusing on optimization of pipeline network, the effect of ownership, and political incentives. In 2008, a paper presented results on case studies demonstrating the economic effects of improving amine capture, developing a competitive oxy-fuel capture, and improving storage monitoring (Jakobsen et. al.) which indicated that improving a technology will indeed reduce the NPV and can be a good indication of the competitiveness of a technology, but the driving force will always be the market conditions (oil, CO_2 price). In 2010, a paper summarized how the methodology was used to explore some of the non-technical aspects of the chain related to technology deployment, specifically on economies of scale in transport pipelines, different scenarios of infrastructure ownership, and government involvement for funding oversized pipelines to promote economic efficiency (Brunsvold et. al. 2011). The main findings in this publication were that benefits from economies of scale increase significantly with pipeline distance, raising the benefits of cooperation from sharing a larger pipeline. In addition, government investment in pipeline infrastructure to build an oversized pipeline as a way to increase economic efficiency and overcome transaction costs corresponds to a lower discount rate and lowers project breakeven costs slightly. In 2011, the focus was placed on coupling power generation (with fluctuating CO_2 emissions) with CCS to reduce CO_2 emissions to demonstrate how CO2 price volatility affects the decision to invest in CCS (Kalinin et. al. 2012). It was shown that there is a trade-off between the price of CO_2 and the cost of CCS technology that determines the specific optimal capacity for CO_2 capture. In addition, increased delays in investment into CCS technologies for a flexible load power plant were found using a multiple time point investment tree model as a result of price volatility compared to the investment in a base load power plant.

The proposed methodology and tool enable the comparison and selection of the most promising options for CCS chains by evaluating the techno-economic criteria. Further, it will reduce the uncertainty related to CCS implementation by improving the understanding of what are the most important parameters, their dependencies, and trends. The proposed methodology has the potential to help to design efficient incentives and measures to stimulate invention, innovation, and realization of CCS by identifying the most important factors affecting the CCS chain viability.

Further research activities include a strong focus on Life Cycle Assessment (LCA) and risk assessment. These issues are dealt with both in the ECCO and the BIGCCS projects.

Information on publications can be found in Appendix 4.

A number of summer job students have performed work under Task E:

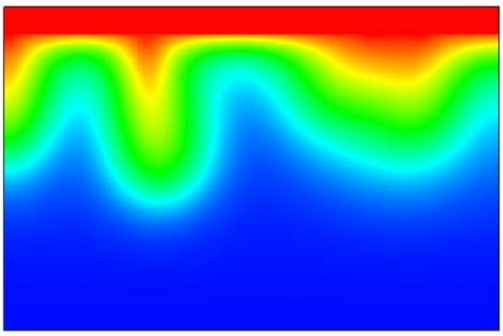
- Øystein H. Nielsen: Extension of the EXPAND tool
- Birgitte Johannessen: Public acceptance of CCS
- Gunnar Håkonseth: Development of new flexible and modular tool CATENA

- Pål Sævik Lode: Development of new flexible and modular tool CATENA
- Hilde E. Sæther: CO2 Value Chain: Analysis of Pipeline Infrastructure for CO_2 Transport
- Alexey Kalinin: Pipeline infrastructure, Flexible power generation, decision tree models.

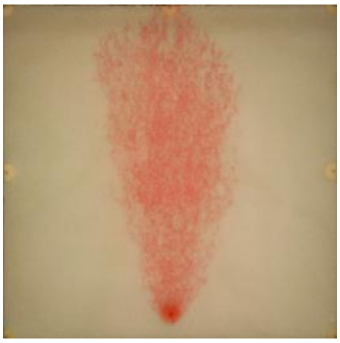
6.6 Enhanced oil recovery and safe underground storage of CO_2 in geological formations (Task F)

Research has been proceeding along several of the main topics of CO_2 geological storage, trying to close some of the knowledge gaps for implementation of large-scale CCS. This summary will touch upon some of the main results.

At the interface between a CO_2 gas cap and the underlying aquifer water column, a boundary layer with denser water will develop, since water with dissolved CO_2 is denser than water without CO_2. At first, the molecular diffusion will dampen the potential instability, but eventually macroscopic convection currents will form. A new formulation for the description of the stability of this boundary layer was developed (Wessel-Berg, 2009). The formulation allows numerical analysis of the time development of this problem for varying anisotropy of the porous medium and gives estimates of the critical time at which the system becomes unstable. The results, have been taken further in the BIGCCS Centre, and will allow better predictions of how long it takes before convection currents forms and hence will lead to improved predictions of long-term storage safety. The results will also allow improved estimates of the effect large grid-blocks have on the simulation of the onset of the diffusion-convection mechanism.



Computer model of convection patterns in water under a CO_2 gas cap (Wessel-Berg, 2009). (Illustration: SINTEF)



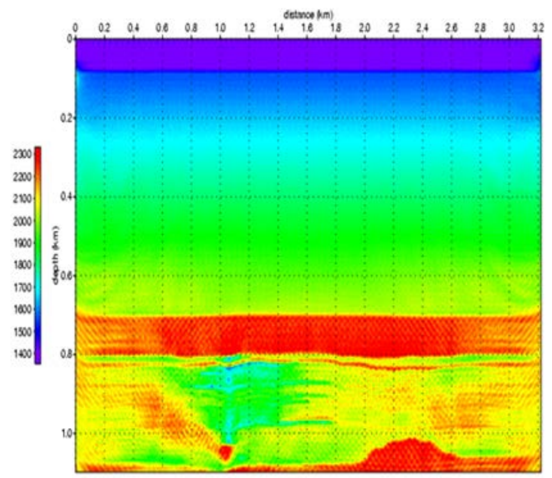
2D-cell experiment illustrating the buoyant migration of CO_2 in an aquifer (Polak et.al., 2010). (Photo: SINTEF)

The diffusion coefficient for CO_2 in water and in some types of oil has been difficult to measure experimentally due to the above mentioned stability issue. Experimental data to constrain correlations has therefore been lacking. Task F has contributed to a refinement of a previously proposed experimental setup for this type of measurements and has tested this for the CO_2-water fluid system.

Leakage of CO_2 from geological storage sites to the surface could potentially compromise climate change mitigation targets. Task F has investigated scenarios for global storage behaviour with respect to leakage and how this could affect the climate. Storage quality becomes more critical for scenarios where more CO_2 is captured and stored and for stricter climate targets (Torvanger et.al., 2012). The studies indicate that the storage quality need to be good enough to keep most of the CO_2 stored for several thousand years. As part of the work supporting these scenarios studies models have been developed for investigation of leakage mechanisms. Detailed modeling using reservoir simulation tools can be used for studies of individual storage sites (Grimstad et.al., 2008). However, for investigation of scenarios involving a global ensemble of storage sites a simplified formulation for each storage site is necessary. For this purpose a simple mass-conservation-based model was developed.

A large fraction of the estimated global geological storage capacity is believed to be in deep saline aquifers in the large sedimentary basins. Many of these sedimentary basins also contain hydrocarbon fields. If large-scale infrastructures for CO_2 capture, transport and geological storage are developed, the possibility of using the capacity of depleted oil and gas fields should also be investigated. Flooding with CO_2 has been pointed to as an enhanced oil recovery option with great technical potential, although case studies for single-field development on the Norwegian continental shelf have not so far concluded positively for CO_2 EOR. To help evaluate large-scale development of CO_2 EOR in the North Sea SPR has developed a model for integrated development of large scale infra-structures for enhanced oil recovery and aquifer storage. Task F has further developed this model to encompass both the Norwegian and UK sectors of the North Sea (Holt et.al., 2009). With the model it is possible to run sensitivity studies on the Net Present Value of large-scale developments with respect to factors such as oil price, CO_2 cost, project life-time, internal project discounting rate, etc.

The seismic monitoring for the Sleipner CO_2 storage site has revealed that the injected CO_2 accumulates in relatively thin layers underneath intra-reservoir mudstone layers. Special processing methods are required to extract from the seismic data sets the necessary detail to resolve such thin layers. In task F, the Full Waveform inversion method has been further developed to be able to work with data sets such as the ones from Sleipner (Ravault et.al., 2009). This work is part of an on-going effort and development and testing on data from real cases are continuing in BIGCCS Centre.



Velocity model from the Full Waveform Inversion method (Ravault et.al., 2009). (Illustration: SINTEF)

Through the cooperation with the Natural Resources law group at the University of Oslo several seminars and workshops have been organized, where legal issues related to transport and underground storage of CO_2 have been discussed. These workshops have attracted interest from regulating bodies and law firms as well as from law students. Several Master theses have been produced through this cooperation (Eilertsen, 2010, Haaver and Bugge, 2007, Hallenstvedt, 2010).

Publications and conference proceedings

Publications from Task F are found in Appendix 4.

6.7 Chemical looping combustion (Task G)

Chemical Looping Combustion (CLC) is a novel technology for CO_2 capture with potential of converting fossil fuels with higher efficiency than conventional combustion. Main activities within Task G have been:

- Identification, evaluation and processing of new oxygen carriers
- Design of a 150 kW CLC research test rig and testing in a cold flow model
- Alternative reactor designs – the rotating reactor concept

Oxygen carrier materials have been developed based on in-expensive industrial tailings, by-products and naturally occurring minerals and ores. A large number of sources have been surveyed. A manganese ore was selected as the most promising for CLC purposes, showing a maximum oxygen capacity of 4.9 wt% at 1000◦C as well as having fast kinetics. Addition of calcium resulted in the formation of calcium manganite perovskite showing potential advantages in terms of kinetics, chemical and mechanical stability. Further addition of titanium resulted in catalytic effects improving fuel conversion. The CLC reactors will demand hundreds of kilograms of oxygen carrier particles. Three different methods for fabrication of oxygen carriers suitable for CLC have been tested and evaluated: spray granulation, spray drying, freeze granulation. Spray granulation/agglomeration show an advantage with easier scale-up.

During the project, SINTEF and NTNU have proposed a new design for a 150 kW CLC reactor system, consisting of two interconnected circulating fluidized bed reactors (CFB's). The viability of the new design has been extensively tested by means of a cold flow model in full scale (i.e. 1:1) of the hot rig design and performance has been evaluated in terms of oxygen carrier circulation and exchange, as well as pressure and concentration behavior. The aimed design condition was achieved with an oxygen carrier exchange of about 2 kg/s. Some drawbacks were highlighted through the tests: the particle concentration up along the FR was too low, and the FR loop-seal was prone to "break-down" creating large particle losses and possibilities for gas leakage between the two reactors. Design modifications were suggested and a rebuild was made. Tests after rebuild show that the system is working much more stable, with increased operability and with higher solid flows and higher solids concentrations up along the reactors. This is especially important for the fuel reactor since it will imply possible higher fuel conversion.

Most CLC designs described are based on fluidized bed technology but in the present task also an alternative concept has been developed. A lab-scale rotating bed reactor for chemical looping combustion has been designed, constructed and tested using a CuO/Al_2O_3 oxygen carrier and methane as fuel. Around 90% CH_4 conversion and >90% CO_2 capture efficiency based on converted methane has been obtained. Potential CO_2 purity obtained is in the range 30-65% - mostly due to air slippage from the air sector, which seems to be the major drawback of the prototype reactor design. Considering the prototype nature of the first version of the rotating reactor setup it is believed that significant improvements can be made.

Task G has contributed to a large increase in knowledge and experience to the BIGCO2 partners about CLC processes, reactor systems and oxygen carrier materials. Both the 150 kW hot rig and a new lab facility for material production and testing is now being built as part of the BIGCCS center. This will ensure a continuation of the work.

Task G has produced six publications in scientific journals, 25 presentations at scientific conferences, one patent and seven presentations/articles in other media (radio, seminars, etc.).

One PhD student, Aldo Bischi, has been educated and has done very good work on the cold flow model testing and design validation and optimization. The thesis was delivered in December and defense will be held when the formal acceptance routines are finalized. Three project and master students have been working within Task G. Prof. Olav Bolland has been the NTNU supervisor for these students.

6.8 Candidate production

BIGCO2 has all together produced eight PhD and Post-Doc candidate. The candidates are listed in *Attachment 3*. Two candidates will complete their projects shortly after the summer 2012, and their reports/thesis will be available during the fall 2012.

6.9 Publications

A total of 123 publications have been produced under BIGCO2. A listing of the publications can be found in *Attachment 4*.

7. Spin-offs and "side-effects"

Undoubtedly, BIGCO2 has yielded more than just the deliverables planned under the project. Below are discussed but some of the more "unplanned" spin-off activities and additional effects of BIGCO2.

7.1 New projects

Even though it is difficult to state with 100 percent certainty that new projects would not have been realized if it wasn't for BIGCO2, it is at least safe to say that BIGCO2 has played an important role as a platform in establishing several new projects. The list below is not exhaustive:

- BIGCCS – International CCS Research Centre (Centre for Environmentally friendly Energy Research – CEER)
- SolvIT
- BIGCLC phase II (KMB project)
- BIGH2 (KMB project)
- CO2 Field Lab

The compound value of the projects listed above is in the neighborhood of NOK 1 billion.

Projects funded by the European Union Framework Programs 6 and 7 include:

- ENCAP (coordinator)
- DYNAMIS (coordinator)
- DECARBIT (coordinator)
- ECCO (coordinator)
- CASTOR

BIGCO2 has yielded several new projects.

7.2 Conferences

BIGCO2 has been instrumental in setting up the series of the ***Trondheim Conference on CO_2 Capture, Transport and Storage* (TCCS)**. The 6th, and so far the last conference in this series, was staged in 2011 with an all-time high in terms of presentations (146 oral presentations, six parallel sessions) and participation (425). The next TCCS will be held in 2013.

Chair of TCCS-6, Dr. Nils A. Røkke, opens the conference. (Photo: SINTEF/Mette Kjelstad)

In 2006, BIGCO2 was one of the main organizers behind the ***Eight International Conference on Greenhouse Gas Technologies (GHGT-8)***. Staged in Trondheim, Norway, the conference drew more than 1000 participants to Trondheim and presented more than 450 technical papers. GHGT is currently the world's largest CCS conference.

7.3 Researcher exchange

Exchange of researchers has been a planned activity in BIGCO2, but the project has also contributed in increasing the general level of personnel mobility from and to SINTEF and NTNU. Some of the internationally renowned institutions BIGCO2 has cooperated actively with are:

- AIST (Japan)
- Aveiro Univ. (Australia)
- Univ. of Berkeley (USA)
- Fraunhofer Inst. (Germany)
- Sandia National Laboratory (USA)
- Technical Univ. Vienna (Austria)
- VTT (Finland)

7.4 Infrastructure

An important part of BIGCO2 has been verification of theoretical results by practical experiments in the laboratory. Very limited funds were at disposal through the BIGCO2 project itself, but additional funding has been secured on the side of the project. Some of the experimental test rigs we have been able to erect with additional funding are discussed below.

HIPPROX – High Pressure Combustion Platform

This facility aims at improving the understanding of combustion for CCS applications particularly, but not exclusively, for gas turbine based cycles. The test rig will allow investigating the unexplored oxy-fuel type of combustion under pressure by targeting engine-near conditions. It will also assess the feasibility of high pressure combustion in oxy-fuel environment through the study of macroscopic flame behaviors such as stability, emissions and heat transfer. The facility can also be used for more fundamental studies of hydrogen combustion at higher pressure, where detailed properties of hydrogen rich fuel flames will be analyzed, as for example lift-off region and strain rates at extinction conditions.

CLC "cold rig"

In fluidized-bed-based CLC, the circulation of oxygen carrier particles between the air and fuel reactor is of major importance for the system performance. This "cold rig" is built as a copy in 1:1 scale of the proposed design for the 150 kW "hot unit". This is a rather large cold rig compared to what is the most usual practice, but give some benefits especially related to reduced wall-effects. The rig has proven to be reliable offering a stable operational window. A sensitive part of the system has been the loop-seals between the reactors. Their role is to separate the gas atmospheres in the two reactors while still circulating the required amount of oxygen carrier. From the tests some design improvements were suggested and the rig was rebuilt accordingly. New tests have shown large improvement with respect to stability of the loop-seals and possible increase in oxygen carrier circulation. Based on the last tests, the design has been frozen and will be implemented in the construction of the hot unit.

Marie Bysveen and Øyvind Langørgen posing proudly in front of the CLC cold rig.
(Photo: SINTEF/Harald Danielsen)

Set-up for characterization of amines

An ebulliometer is a test facility used for characterization and screening of amines. Activity coefficients and amine volatility measurements can be performed in the temperature range 25-170^{o}C with pressures between 0 and 1 bar.

Ebulliometer for characterization of amines.
(Photo: SINTEF)

MMRL - Membranes and Materials Research lab

This facility has been significantly upgraded during the BIGCO2 project period. The facility is used for advanced ceramic materials and membranes for high temperature gas separation and high temperature fuel cell applications. Material synthesis and thorough characterization is covered as well as membrane and fuel cell development and high temperature/high pressure testing of individual components and small modules/stacks.

Gas permeation unit for testing of high temperature dense hydrogen selective membranes. (Photo: SINTEF)

BIGCO2 also paved the way for SINTEF and NTNU's participation in the ***European Carbon dioxide Capture and Storage Laboratory infrastructure*** (ECCSEL), was proposed by NTNU and SINTEF on behalf of the Norwegian Government, and put on the official European Strategy Forum on Research Infrastructures (ESFRI) updated Roadmap in 2008. ECCSEL is planned to be in operation by 2015 as a strong and coordinated pan-European distributed Research Infrastructure within CCS, and started the four year preparatory phase in January 2011.

7.5 International networking

International networking is essential for progress and success in today's world of research and development. BIGCO2 has allowed Norwegian researchers to maintain and significantly expand their international network. In general, BIGCO2 has allowed researchers and key personnel to participate at conferences and in technology networks, and to establish and maintain contact with some of the most renowned research organizations within selected fields of CCS research and development.

European Union activities

During the course of BIGCO2, SINTEF has used the European arena strategically in terms of internationalization. Represented in the board of the ***European Energy Research Alliance (EERA)*** by Ms. Unni Steinsmo (SINTEF CEO), SINTEF has more than its fair share for bringing CCS in as one of six priority areas of the ***Strategic Energy Technologies (SET) Plan***. This activity will continue also after the completion of BIGCO2 since the SET plan is one of the defining documents in terms of Europe's energy policy.

SINTEF is also active in the ***Zero Emission Platform (ZEP)***, which is one of the technology platforms having a direct advisory role to the European Commission. ZEP deals exclusively with CCS, and Nils A. Røkke (Vice-President, climate change technologies, SINTEF) is member of the board.

As a direct result of involvement on the European arena are several ***EU projects funded by the Framework Programme***. SINTEF alone has acted as coordinator for four of these projects. See the listing under chapter 7.1. The compound budget of these projects is approximately € 65 million.

8. Health, safety and environment

At SINTEF nothing is more important that the health and safety of its employees.

During the BIGCO2 project period, the general attention on HES issues in R&D activities at SINTEF has increased considerably. Encompassing many potentially risky laboratory activities, the BIGCO2 project has been a frontrunner in establishing an adequate and stricter HSE regime in SINTEF laboratories.

Experimental test rigs in SINTEF laboratories are now subject to intensive quality control and safety precautions. Each test rig must undergo an independent quality control and approval procedure before experiments can be started. No experiments in test rigs are permitted before a signed ***certificate of operation*** is issued. These certificates are time-limited, and re-issuing requires further control and approval.

Personnel operating test rigs in the laboratory must undergo a general laboratory course, and dependent on the nature of the facility, also take specific courses relevant to the rig in question. All laboratories at SINTEF have been assessed with regard to use of appropriate ***personal protection equipment***. Failure to use such equipment will usually mean that permission to operate test rigs is revoked.

All SINTEF units have implemented ***Synergi*** as an integral part of its systematic HSE work. This is a web-based system where all employees can report on a continuous basis any kind of accidents, near-misses, observations, dangerous conditions, non-conformance, and improvement proposals. When a report is filed in Synergi, relevant project and research managers are automatically informed by e-mail. Whenever such a report has been filed and is relevant to BIGCO2, BIGCO2 meetings will start with a discussion of this issue and conclude with appropriate corrective actions.

No accidents have been reported in relation to BIGCO2 activities. There have, however, been a few incidents, but fortunately with no major negative consequences. A significant amount of undesired conditions and improvement suggestions have been reported.

Attachments

1. Key research personnel
2. Partner organizations and personnel
3. Candidate production
4. Publications
5. Accounting report

ATTACHMENT 1: KEY RESEARCH PERSONNEL

Name	Institution	Task	Main Research Area
Dahl, Paul Inge	SINTEF MK	A	High temperature oxygen and hydrogen membranes
Kim, Inna	SINTEF MK	B	Post combustion CO_2 capture
Ditaranto, Mario	SINTEF ER	C	Pressurised combustion of enriched fuels
Ditaranto, Mario	SINTEF ER	C	Combustion of H_2 rich fuels
Berstad, David	SINTEF ER	D	Power cycles integration and analysis
Jakobsen, Jana P.	SINTEF ER	E	CO_2 chain analysis
Grimstad, Alv-Arne	SINTEF PR	F	Enhanced oil and gas recovery, and storage of CO_2
Langørgen, Øyvind	SINTEF ER	G	Chemical looping combustion

ATTACHMENT 2: PARTNER ORGANIZATIONS AND PERSONNEL

Name	Company	Country
Røkke, Nils	SINTEF ER	Norway
Stori, Aage	SINTEF MK	Norway
Bolland, Olav	NTNU	Norway
Holt, Torleif	SINTEF PR	Norway
Smith, Jens B.	Statoil	Norway
Gonzalez, Miguel	GE Global Research Europe	Germany
Rikheim, Harald	Statkraft	Norway
Graff, Oscar	Aker Clean Carbon	Norway
Tweeddale, Adrian	Shell	Norway
Teigland, Rune	TOTAL	Norway
Danielsen, Jan	ConocoPhillips	Norway
Kaiser, Tony	ALSTOM	Switzerland

ATTACHMENT 3: CANDIDATE PRODUCTION

Ph.D. & Post-Doc Students with Financial Support from the Project

Name	**Nationality**	**Period**	**Sex**	**Topic**
Sevault, Alexis	France	2009-2012	M	Oxy-fuel flame structure
Polak, Szczepan	Poland	2008-2011	M	Storage in aquifers
Farokpohor, Raheleh	Iran	2009-2012	F	CO_2 flow properties in saline Aquifers
When, Xing	China	2009-2012	M	Membrane characterisation
Aronu, Ugoschwukwu E.	Nigeria	2007-2010	M	Solvents
Colombo, Konrad	Germany	2009-2011	M	Membrane power cycles
Sannum, Inge	Norway	2009-2010	M	Oxy-fuel
Eriksson, Annika	Sweden	2009-2011	F	Ceramic membranes

ATTACHMENT 4: PUBLICATIONS

Task A

1. **Dahl, P.I. (2008)**. "Asymmetric ceramic membranes for high temperature oxygen separation". The 10th Int'l Conference on Inorganic Membranes (ICIM-10). Tokyo, Japan.

2. **Dahl, P.I. (2008)**. "Preparation and characterization of mixed conducting oxides for air separation". The 10th Int'l Conference on Inorganic Membranes (ICIM-10). Tokyo, Japan.

3. **Dahl, P.I. (2009)**. "OTM modules: Materials, flux and stability". Euromembrane 2009. Montpellier, France.

4. **Dahl, P.I. (2011)**. "Fabrication, sealing and high pressure testing of tubular $La_2NiO_{4+□}$ membranes". Submitted to Energy Procedia.

5. **Dahl, P.I., M.-L. Fontaine, et al. (2012)**. "Fabrication, sealing and high pressure testing of tubular $La_2NiO_{4+□}$ membranes for air separation." Submitted to Energy Procedia.

6. **Dahl, P.I., M.-L. Fontaine, et al. (2010)**. "Development and testing of membrane materials and modules for high temperature air separation". NAMS/ICIM-11 Conference. Washington D.C., USA.

7. **Dahl, P.I., M.-L. Fontaine, et al. (2011)**. "Oxygen transport membranes - BIGCO2 achievements". The 6th Trondheim Conference on CO_2 Capture, Transport and Storage (TCCS-6). Trondheim, Norway.

8. **Dahl, P.I., M.-L. Fontaine, et al. (2010)**. "Development and testing of membrane materials and modules for high temperature air separation". The 10th Int'l Conference on Greenhouse Gas Control Technologies (GHGT-10). Amsterdam, Netherlands.

9. **Dahl, P.I., M.-L. Fontaine, et al. (2011)**. "Development and testing of membrane materials and modules for high temperature air separation". Energy Procedia **4**: 1243-1251.

10. **Eichhorn Colombo, K., L. Imsland, et al. (2009)**. "Dynamic modelling of an oxygen-mixed conducting membrane and model reduction for control". Journal of Membrane Science **336**(1-2): 50-60.

11. **Fontaine, M.-L. (2008)**. "On the performance of mixed oxygen ion and electron conducting $La_2(Ni,Fe)O_{4+□}$ membranes". The 10th Int'l Conference on Inorganic Membranes (ICIM-10). Tokyo, Japan.

12. **Fontaine, M.-L., P.I. Dahl, et al. (2010)**. "Manufacturing and properties of dense gas separation membranes". Electroceramics XII. Trondheim, Norway.

13. **Håkonsen, S.F., I.M. Dahl, et al. (2010)**. "On the development of a rotating reactor concept for chemical looping combustion – Part 2". The 1st International Conference on Chemical Looping, Lyon, France.

14. **Larring, Y. and P.I. Dahl (2010)**. "Membraner for en renere verden". Teknisk Ukeblad.

15. **Michelsen, F.A., L. Zhao, et al. (2011)**. "Operability analysis and control design of an IRCC cycle HMR unit with membrane leakage". The 6th Trondheim CCS Conference (TCCS-6). Trondheim, Norway.

16. **Paulsen, O. (2009)**. "Rigid bonded glass ceramic seals for high temperature membrane reactors and solid oxide fuel cells". PhD Thesis. Norwegian University of Science and Technology, Trondheim, Norway.

17. **Pavese, F., P.P.M. Steur, et al. (2011)**. "Further results on the triple point temperature of pure 20Ne and 22Ne". The Journal of Chemical Thermodynamics **43**(12): 1977-1983.

18. **Vullum, F., C. Etrillard, et al. (2008)**. "Synthesis and characterization of$Ce_{1x-y/2}La_{xy/2}Ca_yNbO4$ thin film membranes". MS&T'08 Conference. Pittsburgh, USA.

19. **Xing, W., K. Toyoura, et al. (2011)**. "Effects of cation disorder on the solubility and result of doping in oxides". Submitted to International Journal of Hydrogen Energy.

Task B

20. **Aronu, U.E., E.T. Hessen, et al. (2011)**. "Equilibrium absorption of carbon dioxide by amino acid salt and amine amino acid salt solutions". Energy Procedia **4**: 109-116.

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ATTACHMENT 5: ACCOUNTING REPORT

The table below is a *preliminary accounting report*. The report is based on the actual accounting reports submitted to the Research Council of Norway for the years 2007 through 2011.

An amount of NOK 2.100.656 has been transferred to 2012 for completion of two PhD candidates, some other direct expenses, and for finalizing the overall project. This amount is not accounted for in this report. A separate accounting report for 2012 will be submitted to the Research Council of Norway when the project is closed during the fall 2012.

ACTUAL COSTS (NOK)	
Personnel and indirect costs	21.353.705
Purchases of R&D services	64.658.682
Equipment	4.409.737
Other operating costs	13.662.627
Total	**104.084.751**
FUNDING (NOK)	
Host institution	511.410
Private funding	20.338.342
International funding	2.750.000
Research Council of Norway	80.484.999
Total	**104.084.751**

Funding:

The Research Council of Norway

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