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BIGCCS Centre - Supporting large-scale CCS implementation

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Abstract

BIGCCS Centre is an international research centre for CCS as a climate mitigation measure supporting large scale deployment of CO_2 capture, transport and storage by developing new knowledge, fostering breakthrough technology and promoting innovation and value creation at all steps along the CO_2 chain. The Centre is managed by SINTEF Energy Research and involves 22 partners from industry and academia. This paper presents the BIGCCS Centre, the results so far and how in-depth fundamental research contributes to enhancing innovation in the CCS chain.

Keywords: CCS, CO_2 capture, CO_2 transport, CO_2 storage, CO_2 chain, fossil fuels, power generation, industry

1. Introduction

In 2009, the BIGCCS Centre (BIGCCS) was launched as an international Centre for Environment-friendly Energy Research (CEER) [1]. Over eight years and with a total budget amounting to € 45 million, BIGCCS operates as a centre of excellence focusing on CO_2 capture, transport and storage (CCS) research with a clear ambition to move the frontiers of knowledge within several scientific topics and paving the way for sustainable use of fossil fuels in power generation and industry [2]. The vision of the BIGCCS Centre is to join forces between world class researchers, industry and authorities to contribute to the realization of large-scale CCS. BIGCCS has increased the yearly budget from NOK 40 million in 2009 to NOK 70 million in 2012 due to inclusion of four competence building projects, and additional research infrastructure investments.

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International co-operation is key within CCS, the topic is too large and the tasks too complex for one country or one economy to cover. This has been realised in BIGCCS by a true international partnership between both the research partners and the industrial partners.

BIGCCS signify a great boost to CCS research with the emphasis put on advanced basic and applied research. This provides in-depth knowledge and tools pertaining to viable solutions for CO_2 capture in power generation, industry and offshore applications. It covers the whole chain of CO_2 transport, and geological CO_2 storage in an integrated manner. BIGCCS will maintain a continuous focus on result exploration by actively searching for and pursuing opportunities for innovation. Since innovation often proves to occur in the interface between disciplines, BIGCCS enhances the innovative capability of the research community by facilitating work processes that increase interaction across disciplines and expert groups [3].

2. Research approach and results

The research topics covered by BIGCCS require in-depth studies of fundamental aspects related to CO_2 capture, CO_2 transport, and CO_2 storage, relying on a dual research methodology for which both laboratory experiments and mathematical modeling are employed. Through its partners, BIGCCS access comprehensive research infrastructures and several center partners are recognized within advanced modeling and simulation in scientific areas relevant for CCS. Hence, the Center is in a good position to make scientific progress at the cutting edge of CCS technology. BIGCCS has also defined activities dedicated to evaluating the interaction of the investigated technologies and to benchmark various technologies and value chains. BIGCCS is organized in five sub-projects (SPs), as illustrated in Figure 1. In the following, the research tasks of each SP are summarized and some results are presented. Compared to the start in 2009, four new research tasks are now included. These are Task 1.7 BIGCLC (Chemical looping combustion), Task 1.8 CAMPS (international cooperation with Sandia National lab and Berkeley within combustion), Task 2.2 CO_2 Mixture properties and Task 3.4 Caprock properties.

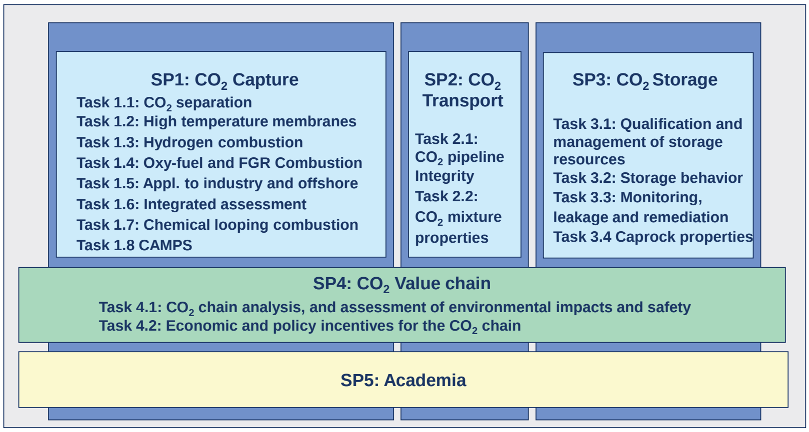

Figure 1: BIGCCS research tasks.

2.1. CO_2 Capture – SP1

Task 1.1 CO_2 Separation: Work is devoted to solvent systems and high temperature particulate CO_2 sorbents. A solvent system model supporting the operation of power plants is implemented to study how the absorber works with variations in flue gas flow [4, 5]. An experimental setup for measurement of vapor-liquid-solid equilibriums has been designed to study the phases formed in precipitating CO_2 capture systems at real conditions [6-10]. For high temperature CO_2 sorbents, the main work has been focused on construction of a high temperature/high pressure test rig for investigations of reaction kinetics and long-term stability of powders in sorption/desorption cycling [11-13].

Task 1.2 High Temperature Membranes: Novel high temperature hydrogen separation membrane materials have been synthesized, characterized, compacted and sintered as dense pellets. The H_2 permeation is investigated at ambient pressure in the temperature range 400-800ºC with a controlled hydrogen partial pressure gradient across the pellet type membrane. Preliminary results, corrected for leakage, indicate a stable and rather high H_2 permeability at temperatures above 400ºC [14-16].

Task 1.3 Hydrogen Combustion: The initial work is to provide a qualitative mapping and quantitative determination of the fundamental processes that characterize combustion of hydrogen-rich mixtures, with focus on stable and safe flame propagation in lean pre-mixed combustion at gas turbine condition. The collaborative work between SINTEF, Technische Universität München, UC Berkeley and Sandia National Laboratories was formalized in 2009. The ongoing R&D activities include: Parallel experimental and modeling investigations of a pressurized version of the *"Berkeley" lifted jet flame* in vitiated co-flow [17-19], direct numerical simulation and experimental investigation with laser diagnostics of hydrogen-air premixed flame propagation in boundary layers [20-23], building on previous work at SINTEF, and finally to contribute to the development of a new Linear Eddy Model (LEM3D) for improved prediction of fuel-oxidizer micro-scalar mixing and combustion in lean pre-mixed mode.

Task 1.4: Oxy-fuel Combustion and Flue Gas Recirculation Combustion: This task focuses on combustion-related technological challenges associated with the implementation of oxy-fuel combustion alternatives for CCS. The main activity has been to specify and design an experimental high-pressure combustion facility dedicated to the study of oxy-fuel combustion in gas turbines (100 kW, 10 bar, multi-CO_2 streams) [24]. A preliminary testing of a light oil burner adapted to oxy-fuel operation is performed and the results highlight the main difficulties of the retrofitting process. Emissions were observed to be comparable to air operation, while the radiative heat flux at the burner increases with O_2 concentration in the oxidant. In any case, further burner optimization is necessary. The third axis of Task 1.4 is to provide inputs and constraints from combustion aspects to Task 1.6 for the analysis and evaluation of novels cycles based on oxy-fuel combustion [25-27].

Task 1.5 Application to Industry and Offshore: The objective is to assess and evaluate the potential for CCS in other industries than power generation, especially offshore-related activities, hence contributing to added value for the Centre partners [28]. The partners are engaged to ensure relevance of the work to be performed, and to ensure sufficient input data for further research. Four cases have been selected; CO_2 capture from gas turbines on floating production storage and offloading units, CO_2 capture from reformer fired heaters in oil refineries, CO_2 capture from aluminium smelter exhaust gases, CO_2 capture from the Kårstø gas processing plant. The integration of this task with the other CCS research topics under *SP1 - CO_2 capture* and *SP4 - CO_2 value chain* has a potential that is exploited in BIGCCS [29-38].

Task 1.6: Integrated Assessment: This task is subdivided into unit design and modeling, process design and benchmarking, and interaction between research tasks. Unit modeling has focused on membrane modeling [39, 40]. Further, a benchmarking methodology is developed [41, 42] and within process design and benchmarking, a reference case is established for gas turbines with EGR [25, 27], carbonate looping [43] and low-temperature CO_2 capture from IGCC [44]. Finally, key parameters, boundary conditions and interdependencies for key processes in Task 1.1 through Task 1.6 are established, based on information gathered from the respective ongoing activities.

Task 1.7: Chemical Looping Combustion: The focus is to bring chemical looping combustion (CLC) technology to the next level of maturity in order to become a competitive option for steam and power generation with CO_2 capture by constructing and building the 150 kW CLC rig [45], building on previous work on a cold-flow system [46-48]. Further, to produce powders in a smaller scale that ensures mechanically robust materials and make an easy scale-up of the production process in the next step.

2.2. CO_2 Transport – SP2

Task 2.1: CO_2 Integrity: The main objective is to develop a coupled fluid-structure *fracture assessment model* to enable safe and cost-effective design and operation of CO_2 pipelines by improving the fundamental understanding of the interaction between the mechanical, thermo- and fluid dynamical behavior [49]. A coupled fluid-structure model is under development [50-53].

Task 2.2: CO_2 Mixture Properties: This task is a KPN-project (competence building project with user involvement), and was established as a spin-off from BIGCCS. The objective is to increase the fundamental understanding of the behavior of CO_2-mixtures under conditions relevant for CCS processes, primarily conditioning and transport. Key tasks are experimental investigations of thermo physical properties of CO_2-rich mixtures, such as phase equilibrium [54-57], density, and speed of sound. The results will be used to improve and extend the range of validity of existing thermodynamic models.

2.3. CO_2 Storage – SP3

Task 3.1 Qualification and Management of Storage Resources: Focus is on improving the modeling of geomechanical behavior during CO_2 injection [58, 59]. The *Snøhvit Field* (Tubåen formation) has been evaluated to test necessary development on secondary migration codes (Pressim and Semi) for modeling long-term CO_2 migration. The Snøhvit Field is believed to be an interesting test case, and this dataset has been released for BIGCCS. Efforts are also devoted to storage site capacity and qualification activities. A review of current approaches for assessing CO_2 storage site capacity has been accomplished. This review will form a basis for more sophisticated dynamic flow simulation approaches for assessing storage capacity [60]. A study on simultaneous CO_2 injection and water production was conducted for optimizing the exploitation of CO_2 storage resources [61]. A number of large-scale flow models of *Bunter Sandstone* (UK sector of North Sea) have been generated. The models assess the impact of boundary conditions, particularly at regional scale [62]. Results from dynamic simulations are compared with estimates derived by existing static methods to determine the validity of static approaches for open, closed and semi-closed systems. Simulations show that the aquifer pressure evolution is fast and the pressure wave extends far away from the injected CO_2 plume [63].

Task 3.2 Storage Behavior: Both experimental and theoretical studies of geochemical and geo-mechanical effects of CO_2 on the cap rock and reservoir are on-going. BGS has carried out a set of long-term batch experiments to assess the reactivity of CO_2 and pore-water with Sleipner cap rock and wellbore materials. Tests have been running since July 2005, and will be continued to provide the longest experiments yet undertaken (up to 7 years). SINTEF has carried out punch testing of shale samples in order to quantify the effect of CO_2-water on cap rock strength [64]. GEUS has conducted experiments to study drying-out effects on various minerals and under varying conditions. Also, a study of diffusion induced convection mechanisms in presence of heterogeneities has been performed. This study extends former work on the gravitational instability of a diffusive boundary layer in a semi-infinite anisotropic porous medium. This instability behavior should be seen as an upside for underground CO_2 storage, as dissolution is an important aspect for retaining the CO_2 in the underground for thousands of years [65]. The *Pressim* software has been evaluated for modeling the effects of CO_2 on pressure [66]. Further gas-oil gravity drainage in fractured carbonate rock subjected to gas injection has been studied [67].

Task 3.3 Monitoring, Leakage and Remediation: Several monitoring tools and models for CO_2 injection and storage are developed and tested; i.e. *CSEM* (Marine Controlled Source Electro Magnetics) [68], and the *FWI* (Full Waveform Inversion). A gravity modeling study was made to estimate if 4D CO_2 effects can be observed using gravity data. Results indicate that a CO_2 reservoir can be monitored over time. Accurate mapping of the development of reflectivity in the CO_2 Sleipner plume and also the velocity pushdown on deeper layers beneath the plume are challenging. So far horizons and pushdown up to the 2006 survey are mapped. Time-frequency spectral decomposition techniques have been applied to the time-lapse surface seismic data (3D and high resolution 2D) at Sleipner. Application of this tool to the topmost layer on the 2006 dataset reveals strong tuning effects and the capability of mapping travel-time layer thicknesses. GEUS is developing a catalogue of reservoir models, using conceptual structure and actual data from geological settings giving rise to layered reservoirs, e.g. fluvial systems and near-shore depositional systems with sea-level fluctuations. Initial laboratory tests have been performed at SINTEF to measure wave velocity changes and strain response to stress changes that mimic those occurring within a storage site and in the cap rock above it, for scenarios reproducing CO_2 injection and CO_2 leakage [69].

2.4. CO_2 Value Chain – SP4

Task 4.1 CO_2 Chain Analysis, Environmental Impacts and Safety: The aim is to develop a common framework for CCS chain assessment including analysis of techno-economic criteria, risk, and environmental impacts associated with CCS chains [70]. The main achievement is a methodology developed for multi-criteria analysis of CCS chains [71]. The objective for the methodology is to enable fair comparison of various CCS projects based on integrated assessment of economics, environmental impacts, and associated risks taking into account also the economic, societal, and political environment of the CCS chain. The method has been used for comparing two transports technologies for a case study in which 10 Mt/y of CO_2 from an industrial cluster are transported over 500 km by onshore pipeline and CO_2 shipping [72] as well as for other applications [73-75].

Task 4.2 Economy and Policy Incentives for the CO_2 Chain: The aim is to develop scenarios for CCS development and deployment and to develop a stochastic model for investment decisions. This work will improve stakeholders' understanding of possible future value of CCS technologies and therefore provide a better knowledge basis for investments in R&D, pilots and large-scale CCS [76, 77]. An economic model has been developed to analyze stakeholders' understanding of CCS technologies and related uncertainties.

2.5. Academia – SP5

23 PhD students and eight post docs are planned in BIGCCS. The Norwegian University of Science and Technology (NTNU) is responsible for this sub-project and most of the students. Further, University of Oslo (UiO), the Technische Universität München (TUM), University of California, Berkeley and Ruhr-Universität Bochum are involved with PhD students. The students do their research in close collaboration with their supervisors and the respective research tasks with access to infrastructure and resources in BIGCCS. Currently, 18 PhD students and five post docs have started their work.

3. How in-depth fundamental research contributes to enhance innovation in the CCS chain

By conducting targeted long-term research in the early phase of the innovation chain, BIGCCS will provide future opportunities for new products and new solutions for CCS. Figure 2 (next page) illustrates the position of the Centre in the innovation chain and indicates the role of BIGCCS being a driving force in accelerating the development and deployment of CCS technology. The expectations to the BIGCCS Centre are many and the two most clearly expressed are to conduct fundamental research in the forefront internationally and to contribute to innovation and implementation of large-scale CCS.

From the beginning in 2009, an important intention with BIGCCS has been to expand the level of activities. During the three fist years of operation, the annual budget is increased from ca. NOK 40 to NOK 70 million due to four more competence building projects and significant infrastructure funding.

BIGCCS is fortunate to have a surplus of industry funding as related to the requirements set by the Research Council of Norway (RCN). This surplus funding has been used to apply for additional competence building projects (KPNs) from the RCN. So far, the following four additional competence building projects have been granted.

- CO2Mix: Investigations of fundamental properties of a variety of CO_2 mixtures
- BIGCLC Phase 2: Development of circulating looping combustion
- CAMPS: International cooperation for world-leading combustion modeling
- Caprock Properties: Investigation of fundamental effects of CO_2 on reservoir and caprock properties in connection with CO_2 storage

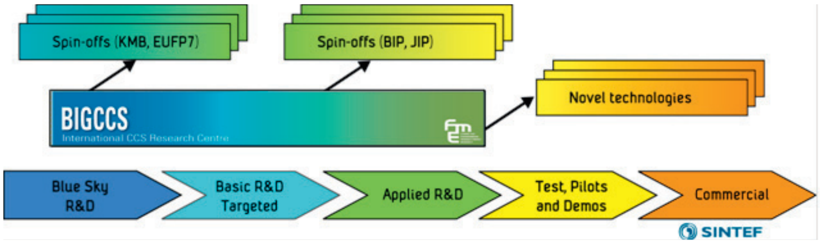

Figure 2: The role and position of BIGCCS in the innovation chain [2].

The CEER scheme opens for applications for infrastructure complementing the activities under the centers. Typically, such funds should be spent on infrastructure positioning the Center in the R&D front. So far, BIGCCS has been granted more than NOK 20 million. In particular, investments have been made in a test-rig for oxy-fuel combustion, a test-rig for investigations of fundamental properties, a rig for development of membranes, and on equipment monitoring different aspects of CO_2 storage.

In addition to the activities mentioned above, several new projects have been established. They are typically related projects in terms of scope, but not formally associated with the Center. BIGCCS has fostered an EU FP7 project; IMPACTS which is established in 2012. Also, several innovation projects with fewer partners have been launched from the BIGCCS Centre.

7. Conclusion

In 2009, BIGCCS Centre was launched as a comprehensive collaborative research effort bringing together 22 industry companies and academic institutions with the ambition to advance technology at all steps of the CO_2 chain. After tree year of operation the organization that constitutes the BIGCCS Centre has settled, adequate work processes are established and the research activities are producing valuable results. For instance, within CO_2 capture preparatory experimental work is carried out to investigate equilibrium measurements for post-combustion solvents, kinetics and stability of CO_2 sorbents, H_2 permeation of high temperature H_2 membranes, and fundamental processes that characterize H_2 and oxy-fuel combustion. In addition, major efforts are put into modeling, simulation and analyses of all capture technologies to be explored. The ground-breaking work on the integrity of pipelines for CO_2 transport is progressing well together with the activity on CO_2 mixture properties that are about to start generating new data. Within CO_2 storage, experimental activities on storage behavior and monitoring are well underway and accompanying work on modeling and simulation has started. Dynamic simulations are carried out to investigate aquifer pressure evolution to enable improved modeling of geomechanical behavior during CO_2 injection. In CO_2 value chain, work is progressing to develop a common framework for CCS chain assessment, including techno-economic criteria as well as risk and environmental impacts. Finally, potentials of CCS to reduce global CO_2 emissions are investigated together with issues such as dependency on major economic and political conditions and the value of flexibility in the CCS chain. Education and competence building is a key issue for development and implementation of CCS.

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