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Energy Procedia 4 (2011) 6077–6084

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-10

BIGCO2 R&D Platform
Breakthrough CCS technologies enabling large-scale CO_2 chains

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Abstract

The paper presents the structure and achievements of the BIGCO2 R&D Platform, an international collaborative research project aiming at developing several enabling technologies and innovative solutions supporting a large-scale deployment of CO_2 capture from power generation and underground storage of CO_2. All main routes for CO_2 capture are investigated, and emphasis is put on combining experimental work with theoretical analyses. The project is coordinated by SINTEF Energy Research and the budget of the current project period (2007-2011) is 16 M€.

Keywords: CO_2 capture; CO_2 storage; CO_2 chain; CCS; sustainable power generation

1. Introduction

The BIGCO2 R&D Platform (BIGCO2) builds knowledge and technology underpinning demonstration of power generation with carbon capture and storage (CCS) at industrial scale. The project aims at closing several critical knowledge gaps of the CO_2 chain to enable sustainable power generation from fossil fuels based on carbon capture and safe underground storage of CO_2. Taking the first phase of the project into account BIGCO2 is the largest publicly funded research project on CCS in Europe. Hence, BIGCO2 is a unique project in terms of its size, its diversity and the fact that it comprises the whole CO_2 chain. The project is set up as a an extensive international collaborative effort bringing together the expertise and research infrastructure of competent research institutes and universities, supported by leading vendors, energy companies, oil and gas companies. The paper presents the BIGCO2 project, discusses its scientific achievements, and outlines how the project results can contribute to large-scale deployment of CCS.

2. BIGCO2 objectives and facts

The purpose of BIGCO2 is to complement and extend knowledge developed in the forerunners of the project and in other ongoing research programmes to enable power generation with CCS. Tangible objectives are **90 % CO_2 capture rate**, **50% cost reduction** and **a fuel to electricity penalty less than 7 %** compared with state-of-the-art power generation. Emphasis is put on advanced basic and applied research providing breakthrough knowledge and solutions

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doi:10.1016/j.egypro.2011.02.613

paving the way for environment-friendly and profitable power generation based on fossil fuels. BIGCO2 (www.bigco2.com) is coordinated by SINTEF Energy Research. Other partners of the BIGCO2 Consortium are Statoil, GE Global Research, Statkraft, Aker Clean Carbon, Shell, TOTAL, ConocoPhillips, ALSTOM, DLR, TUM, NTNU, CICERO, SINTEF Materials and Chemistry and SINTEF Petroleum Research. The University of Oslo is a subcontractor of the project. Further, BIGCO2 benefits from a strong collaboration between the combustion research facility at Sandia National Laboratories (USA) and SINTEF Energy Research. The main sponsors of BIGCO2 are the Research Council of Norway and Gassnova, with considerable co-funding from the industry partners. The total budget for the current project period of BIGCO2 (2007-2011) is 16 M€.

3. R&D challenges addressed by BIGCO2

BIGCO2 includes research activities related to the main CO_2 capture routes; post-combustion, pre-combustion, oxy-fuel and Chemical Looping Combustion (CLC), illustrated in Figure 1. A portfolio of capture technologies are investigated including novel combustion systems, advanced materials, innovative CO_2 capture technologies, integration of novel technologies in power cycles and analysis of power cycles performance (Task A through D and G). In addition, there is extensive activity related to enhanced oil and gas recovery with CO_2 and safe underground storage of CO2 in geological formations (Task F). Finally, CO_2 chain analysis is included to evaluate the whole CO_2 chain with respect to technology, economy and environmental impact (Task E). The scientific focus of the project is defined based on the identified long-term research needs pointed out by e.g. the European Technology Platform for Zero Emission Fossil Fuel Power Plants (www.zeroemissionsplatform.eu), the research areas where the research providers of the project have proved to be in the scientific forefront and the topics in which the industry partners have commercial interest. Section 5 presents the results from each research task of BIGCO2.

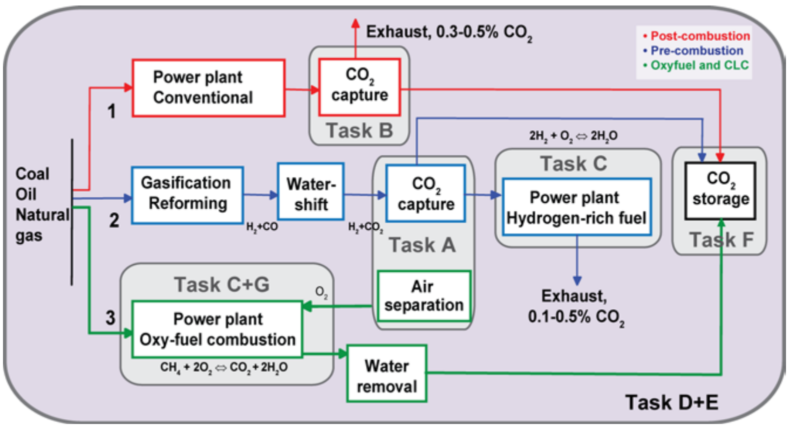

Figure 1: Scientific focus of BIGCO2 with reference to research tasks.

4. Research approach

The scientific ambition of BIGCO2 is to conduct high quality research within selected topics, push science beyond the state of the art and serve as a basis for innovation. In the project, principal research is executed at a level of detail spanning from molecular reaction kinetics to CO_2 chains and global climate effects. To a large extent theoretical analyses are accompanied by experimental studies and demonstrations. To some extent laboratory set ups are built specifically for the purposes of the project, e.g. cold and hot rigs for CLC experiments, oxy-fuel and hydrogen combustion test rigs, experimental set up for testing high temperature membranes and laboratory for exploring CO_2 storage in geological structures. In addition, the project makes extensive use of the existing laboratory infrastructure available among the partners of the project and promotes close interaction between the partners to release the full potential of this scientific partnership. A comprehensive educational program is part of BIGCO2, including 11 concluded and 12 on-going PhD fellowships, 11 post docs and several research visitors. The educational program contributes with fundamental research and will in the long run enable industry and research institutions to recruit competent researchers to the growing field of CCS.

The project is organised in 8 tasks. Figure 2 indicates the research areas of BIGCO2 and illustrates how the tasks relate and interact.

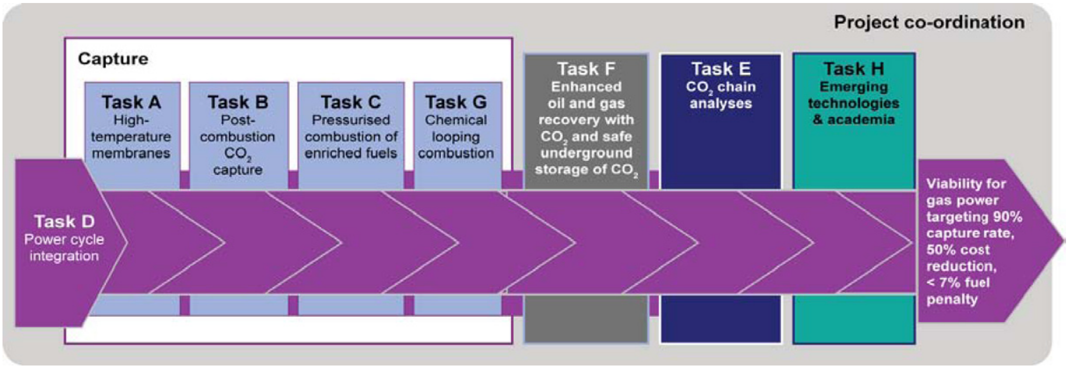

Figure 2: BIGCO2 research tasks.

5. Results

Below the main results from the research tasks in BIGCO2 are summarized and selected references are included.

CO_2 capture technologies

BIGCO2 includes activities related to post-combustion, pre-combustion, oxy-fuel and CLC for CO_2 capture, as well as enabling technologies such as high temperature oxygen generation and systems integration. Five tasks in BIGCO2 focus on topics related to CO_2 capture: Task A - Task D and Task G.

Task A: High temperature membranes for clean power production

Gas and coal power plants world wide require cleaner combustion and less emission. Several different technologies are under development to facilitate this and oxygen transport membranes (OTM) is one of them. OTMs can separate oxygen from air with 100% selectivity. The high operating temperatures make OTMs particularly promising for integration in power plants to facilitate combustion in pure oxygen (oxy-fuel combustion). The exhaust gases of such a process will consist of only CO_2 and steam which can be easily separated, and hence give a power plant with 100% CO_2 capture. Access to oxygen at a lower cost is also a key to reducing the costs related to natural gas reforming and gasification which are parts of pre-combustion CO_2 capture.

In BIGCO2 Task A, large efforts are put on the development of OTM materials and scalable methods for manufacturing membranes. From starting with fabrication and testing of planar membranes of ~1cm^2, tubular membranes are currently assembled. Silver based brazing is used to seal tubular OTMs to high temperature alloy caps attached to steel gas pipes. These pipes transport the permeated oxygen out of the module for instance by a sweep gas. The oxygen flux of the OTMs has been measured at high temperatures (600-1000°C) with promising results. As the flux decreases with increasing membrane thickness, the membranes are manufactured with an asymmetric architecture. This means that a dense membrane layer is prepared on top of a porous support; the latter should not restrict the gas flow and assure sufficient mechanical strength. The increased flux using this concept has already been demonstrated for small planar membranes and is currently under investigation for tubular membranes. [1-5]

Task B: Improved post-combustion CO_2 capture by novel solvents development and system modelling and simulation

Post combustion CO_2 capture by chemical absorption is a subject under rapid development, since this is the only technology presently available for large scale CCS. The overall goal of Task B is to reduce the energy consumption for this technology to <2.5 GJ/ton CO2 captured, while at the same time reducing amine losses and waste production by 50% and equipment cost by 30% and the main focus is on novel solvents development and system modelling and simulation. A critical issue is to increase the understanding of the chemistry and thermodynamics of the process is required as an improved description of the chemistry is important both in the development of solvents and in improving process modelling tools applied for process optimization and operation,

To describe a solvent system data on a number of properties is required: phase and chemical equilibrium data, reaction kinetics and equilibrium constants in the system. In BIGCO2, work is carried out on screening and characterization of new candidate solvents [6-10], measuring reaction kinetics [11-12], phase equilibria [13-15] and enthalpy of absorption [16,17] for a number of solvents. The work also includes molecular simulation and test of the candidate solvents at pilot plant. Further, development of thermodynamically consistent model [18,19] for CO_2 capture as well as process modelling [20,21] is important for design and operation of the industrial units. Dynamic modelling and simulation are crucial activities to understand the capture process under transient conditions [22,23]. Transient conditions occur normally during start-up and shut-down, but many power plants are operated at varying load meaning that the inlet conditions for the capture plant will change continuously. Currently, the study of related environmental issues is an important activity in the project. For instance, daphnia toxicity are investigated and fate studies are carried out.

Task C: Pressurised combustion of enriched fuels enabling hydrogen and oxy-fuel combustion
Task C includes combustion research at SINTEF Energy Research, DLR (Stuttgart, Germany), the Technical University in Munich. The overall objective of the task is to advance the fundamental understanding of combustion applied to power generation processes with CO_2 capture and to develop improved numerical and experimental tools to facilitate development of new concepts and validation of hydrogen and oxy-fuel combustors and their operational behaviour. While the processes for post-combustion are mainly based on conventional combustion technologies, the alternative routes, pre-combustion and oxy-fuel, represent great challenges that are addressed by Task C.

Oxy-fuel combustion is a new field and a special effort is put on experimental studies of basic properties of combustion. The global behaviour of laboratory scale flames is investigated as a function of CO_2 dilution of the oxygen. The stability regimes are mapped for the lifted and swirl flames, and the radiative heat flux profiles of methane flames in varying O_2/CO_2 environment have been quantified and compared to air supported combustion. Fundamental properties like laminar flame speeds and ignition delay times have been measured at varying pressure and O_2 concentrations and compared to the numerical solutions based on various kinetic mechanisms [24-27].

For the pre-combustion applications, hydrogen combustion is investigated on several fronts. The challenges in using hydrogen as a fuel reside in its high reactivity when in contact with hot air, preventing the use of conventional low NOx burner technology. A necessary step to conceive appropriate burners is to fully predict the mixing of hydrogen. A recent mixing model (Linear Eddy Model) has therefore been further developed in collaboration with SANDIA National Labs and is implemented into a RANS/EDC based CFD. Experimentally, the sensitivity of hydrogen flames to flashback through boundary layers is investigated in order to better understand the underlying physics responsible for this particular phenomenon. Finally, theoretical chemical kinetic studies of intermediate reactions of the hydrogen combustion mechanism have been performed [28].

By achieving the goals set forth in Task C, necessary knowledge on combustion performance and the pollutant emission threat will be gained to support the design of oxy-fuel and hydrogen combustion systems.

Task G: Chemical looping combustion (CLC)
Chemical Looping Combustion (CLC) is a fuel conversion technology with a potential of converting fossil fuel with higher efficiency than conventional combustion and with CO_2 separation partly inherent in the process. In CLC, the air and fuel are not mixed. An oxygen carrier material is continuously looped between two reactors transporting oxygen from the air reactor to the fuel reactor where the fuel is oxidized. The fuel reactor exhaust contains only CO_2 and water vapour which can easily be separated by condensation. Major challenges of CLC are related to the reactor design and to the oxygen carrier materials in order to achieve continuous long-term stable operation with high fuel conversion. This is the motivation and the basis for the Task G activities on CLC.

A 150 kW_{th} reactor system of two connected circulating fluidised beds (CFB) has been designed and engineered and will be built in the laboratories of SINTEF/NTNU. [29,30]. A cold flow model in scale 1:1 was built in 2009 and is being used to test hydrodynamics and oxygen carrier circulation [31,32]. Key design features are:

- Industrial applicability and scalability - industrial CFB solutions where possible
- Flexibility – different type of oxygen carrier materials and operating conditions
- Compactness – for minimum oxygen carrier inventory and for placement into a vessel in order to operate at elevated pressure planned for the last project phase
- Process control measures for long-term continuous operation

The oxygen carrier materials being developed in Task G are based on in-expensive industrial tailings and by-products. The aim is to achieve high oxygen capacity and mechanical and chemical stability for long-term operation at the high temperatures (~1000°C) and the cyclic environmental conditions (air/fuel reactor) in a CLC laboratory set up. A manganese ore with addition of calcium to form a perovskite phase has been selected as the most promising from a large number of materials initially tested [33].

Most of the CLC demonstration work today is on CFB kind of reactors. In a longer term more compact reactors may be developed using a rotating reactor concept. At present the Task G is developing such a concept and a laboratory scale prototype reactor has been built and is now being tested. Since the oxygen carrier bed is rotating, one of the critical points is to avoid mixing between the gas streams [34].

Task D: Power cycle integration and analyses including unit modelling and simulation
Due to high efficiency and low carbon intensity in the fuel, modern natural gas-fired power plants emit less CO_2 per kWh of produced electricity than coal-fired power plants, but will still have to be cleaned of CO_2 as part of the global effort for reduced emissions. While BIGCO2 as a whole mainly focuses on developing technology to enable clean power production from fossil fuels, the main function of Task D is to investigate the application and integration of novel capture technologies in overall power plant processes. In this evaluation, the feasibility of new technologies must be assessed against several criteria such as energy efficiency, process control, techno-economic performance, reliability and availability. A challenge in the evaluation of the potentials of novel capture technologies is the fact that the processes in consideration to a large extent have not yet been built, at least not in the required scale. This necessitates the use of process simulation tools to represent possible configurations of the capture processes. In Task D, a benchmarking method is developed [35,36] and the CO_2 capture technologies focused on in BIGCO2 are assed in a process perspective to reveal new knowledge related to research challenges and opportunities within the technologies [37,38].

In addition, a macroscopic flow model for a CFB-CLC unit is implemented by Task D. The model is object oriented and based on semi-empirical correlations and its purpose was to investigate where the unit has stable operation points and forms a basis for more detailed reactor models that will include mass and energy balance and chemical reaction kinetics. The results from the model development and simulations were valuable inputs to the process of designing the CFB-CLC reactor in Task G [39].

CO_2 chains ***Task E: CO_2 chain analyses***
BIGCO2 is developing a modelling framework for evaluating viability of large-scale CCS chains taking technical, economical and environmental aspects into consideration in a consistent and transparent way [40]. In addition, conditioning and infrastructure for CO_2 transport are investigated. The activity on CO_2 chain analyses formed the basis for the development of the EU FP7 project ECCO [41]. Lately, case-studies on CO_2 transport infrastructure are carried out. Focus has been optimization of pipeline network, effect of ownership and political incentives [42].

CO_2 storage ***Task F: Enhanced oil recovery and safe underground storage of CO_2 in geological formations***
In Task F, options for safe CO_2 storage in aquifers and depleted oil/gas fields are investigated and fundamentals related to CO_2 for EOR are studied [43-45]. The project also includes analyses of global climate effects of various leakage scenarios and legal/institutional aspects of CO_2 management are investigated [46]. Increased knowledge on all relevant aspects of geological storage of CO_2 will provide a better foundation for establishing a common regulatory framework for CO_2 storage, thereby enabling a stable environment for sound, long-term business decisions.

A recent result of Task F is an improved theoretical description of the stability of the diffusive boundary layer between a CO_2 gas cap in a saline aquifer and the water column below [47-48]. When CO_2 is injected into a saline aquifer it will rise to the top of the formation due to its buoyancy with respect to water. Over time the CO_2 will gradually diffuse into the water column below. Since water with dissolved CO_2 will increase in density, this creates an unstable situation and eventually convective currents will arise, transporting dissolved CO_2 into the deeper parts of the aquifer much quicker than what can be achieved with diffusion alone. Due to the negative buoyancy of CO_2 dissolved in water, this is considered to be a very safe storage situation. The work has established a new formulation of the time development of the diffusive layer, enabling calculation of the time before onset of convection for anisotropic porous media.

6. Spin-off effects and implications for CCS deployment

Norway is an early mover within CO_2 capture and storage. Since 1996, Statoil has injected CO_2 from the Sleipner gas field in the Utsira formation reducing the annual CO_2 emissions by nearly 1 M ton and providing unique knowledge regarding processing and injection of CO_2. When is comes to CCS research SINTEF and NTNU have been pioneers. SINTEF Petroleum research early identified CO2 storage as an option for reducing CO2 emissions. SINTEF Energy Research and SINTEF Materials and Chemistry jointly with NTNU systematically have built competence on a range of CO_2 capture technologies and integrated power cycle analysis. The 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. The project and its predecessors have resulted in progress within multiple research areas related to CCS and have led to several new projects building on the results and knowledge achieved in BIGCO2. Most recently, the international research centre BIGCCS was launched in 2009 involving 22 research and industry partners and a total budget of 45 million € over 8 years [49]. Other examples are SOLVit, CO_2 Lab Field, and BIGH2 Innovation, all with considerable financial support from the public research programme Climit in addition to industry funding. The Trondheim CCS Conference (TCCS) has become a leading scientific CCS technology conference and is organised every second year. In addition, several EU projects such as DECARBit and ECCO, are established by SINTEF in collaboration with international research and industry partners.

BIGCO2 focuses on establishing the scientific foundation for new knowledge and technology, paving the road for sustainable power generation with CCS at reduced costs and with acceptable environmental impacts. By conducting targeted long-term research in the early phase of the innovation chain BIGCO2 can provide future opportunities for new products and new solutions for CCS. Figure 3 illustrates the role of the project in the innovation chain and some Norwegian examples are included.

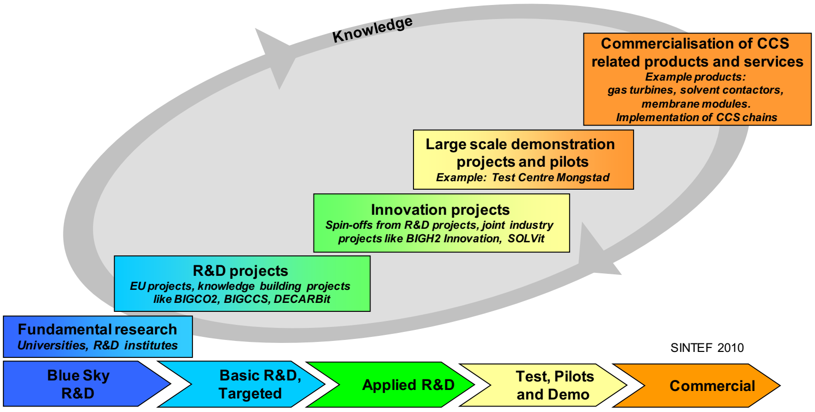

Figure 3: Knowledge building projects (R&D projects) as part of the innovation chain.

The **blue sky R&D** activity is mainly conducted by the universities and includes research and education focusing on aspects like fundamental physical and chemical properties. The work is usually publicly funded and implies high risk with respect to short or medium term commercial benefit, but can provide breakthroughs that represent step changes within various technologies. **Targeted basic R&D** is mainly conducted by research institutes and universities and to some extent industry companies. The projects develop knowledge and technology underpinning new solutions to identified challenges that are far reaching and the project consortiums include several industry companies and public bodies in addition to the research institutes. BIGCO2 is a major project in this category. EU FP6 and EU FP7 comprise a long list of R&D projects focusing on CCS such as ENCAP, CASTOR, DYNAMIS, CO2 REMOVE, ULCOS and CO2 GEONET (EU FP6) and ECCO, DECARBit, CESAR and CEASAR (EU FP7). These extensive collaborative undertakings enable coordination of research activities, facilitate information exchange and educate experts that can be recruited by industry and academia. **Applied R&D** includes the innovation projects of a more competitive character. The projects are usually more focused, closer to the possible future commercial products and involve fewer partners than the basic R&D projects and the extent of industry participation and funding is larger. Many innovation projects make use of results such as competence and research infrastructure developed in basic R&D projects and some projects are spin-offs from ongoing research projects. One example related to BIGCO2 is the project **BIGH2 Innovation** aiming at developing a new generation of hydrogen-powered gas turbines. Another example is the eight-year science research and development program **SOLVit** launched by Aker Clean Carbon, SINTEF and NTNU. SOLVit aims to generate better and more cost effective processes and chemicals to manage CO_2 emissions from power generation and industry, and results from BIGCO2 and related research projects served as starting point for the new program [10].

Next phase of the innovation chain is **large scale tests, pilots and demonstrations** where a consortium can be set up by energy companies, technology manufacturers, vendors and possibly governmental bodies when public funding is included. Often research partners are included as well for integrated research activity. The objective is to further develop and demonstrate viability of new technology and make possible commercialization at reduced risk and lower cost. One Norwegian example is the Mongstad project preceded by the **European Test Centre Mongstad** where post-combustions technologies will be further developed, tested, and qualified at large scale before a full scale implementation is carried out to capture flue gases from Mongstad's combined heat and power plant (investment decision 2014). The final phase of the innovation chain is the product development conducted by technology manufacturers and vendors aiming at **commercialization** and thereby widespread dissemination of the proven technology. Examples of CCS related products are solvent contactors, gas turbines and membrane modules. By developing and validating CCS technologies research projects can strengthen the competitiveness of related industry and result in value creation based on new products and services. However, profitability is a prerequisite for industrial uptake of new technology, independent of the noble intentions of developing technology for preventing climate change.

As illustrated by this review of a simplified innovation chain, BIGCO2 can promote the large scale deployment of CCS by developing knowledge and technology critical for the commercial actors in their efforts to create the products required for cost effective solutions for sustainable power generation with CCS. Application of new technology will reduce the emissions in the western part of the world and transfer of new technology to developing countries will be a premise for global reduction of GHG emissions. Besides technology development there are critical frame conditions that must be in place to enable large scale CCS. First, an international agreement must be reached regarding the global ambitions for emission cuts and how the cuts should be financed. Second, there are several legal and institutional issues to be resolved in order to implement CO2 chains across borders with large scale CO2 storage sites.

7. Conclusion

The BIGCO2 R&D Platform is a comprehensive, international collaborative research project and the paper illustrates how BIGCO2 contributes to enabling large scale CCS. First, the paper's review of the scientific progress in BIGCO2 documents that new knowledge is developed supporting all CO_2 capture routes and underground CO_2 storage. Further, it is pointed out that the education program of BIGCO2 will result in a total of 23 completed PhDs and that the project has already resulted in several spin-off projects. Finally, experience shows that by involving industry partners in research projects and innovation activities it is possible to promote the competence building and targeted technology development required for the implementation of large scale CCS. Scientific progress, education and industry uptake are critical to accelerate the CCS deployment and BIGCO2 contributes to all.

8. Acknowledgements

This publication forms a part of the BIGCO2 project, performed under the strategic Norwegian research program Climit. The authors acknowledge the partners: Statoil, GE Global Research, Statkraft, Aker Clean Carbon, Shell, TOTAL, ConocoPhillips, ALSTOM, the Research Council of Norway (178004/I30 and 176059/I30) and Gassnova.

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