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BIGCCS Innovations – Measures to accelerate CCS deployment

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Abstract

After six years in operation, BIGCCS International Research Centre is in its final phase, and results are being produced at high speed. The ultimate goal for the BIGCCS centre is to contribute to the acceleration of deployment of CCS technologies. Therefore, the Centre has put considerable emphasis on generating useful results to its industrial partners, and results with a significant potential for commercialization. The paper describes 22 of the most promising innovations identified under the Centre. These 22 innovations are related to capture, transport, storage and value chain, and are but a few of all potential innovations identified. The paper also discusses how BIGCCS has managed innovations, which are classified according to a nine-point Technology Readiness Level scheme.

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Keywords: BIGCCS; Innovation; Results

1. Introduction and background

The BIGCCS Centre [1] was established in 2009 under the Norwegian Research Council's scheme Centres for Environment-Friendly Energy Research (CEER/FME) [2]. The primary objective of the scheme is to establish time-limited research centers which conduct concentrated, focused and long-term research of high international caliber in order to solve specific challenges in the field. This objective includes both a focus on high-risk, long-term basic activities and on producing useful results for the industry partners. Consequently, *innovation* has held a central position in the Centre's portfolio of activities throughout its period of operation.

Innovation opportunities are developed between researchers and industry partners. In this respect, technical meetings at BIGCCS task level, between the researchers and industry partners, is an important arena. Here the researchers present ideas and opportunities for the industrial partners and the industrial partners can respond and give advice and corrective input to the researchers for further priorities. Feedback from the technical meetings in terms of well-anchored annual working plans and special reports on innovations are given back to the BIGCCS Board, which discusses innovation opportunities regularly. Innovation is also a frequent item on the agenda of the Centre Management Group meetings, and as technology has matured, the tendency has been to give

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increasingly more attention to bringing ideas out to the industrial partners. Furthermore, the BIGCCS Center is set up with and Exploitation and Innovation Advisory Committee, which assists in questions related to innovation opportunities. The committee has regular meetings and can also call for ad-hoc meetings for discussion of innovation possibilities.

Most of the BIGCCS innovations are still classified with a TRL level up to 5 (precompetitive research). This means that the "ownership" of different innovations will now be shifted from the research partners to the industry partners. In this process assistance will be sought from professional innovation actors, such as for instance the Technology Transfer Office at NTNU. The result could be that ideas are still kept and further developed between two or more BIGCCS partners, or ideas could be "sold" to companies outside BIGCCS.

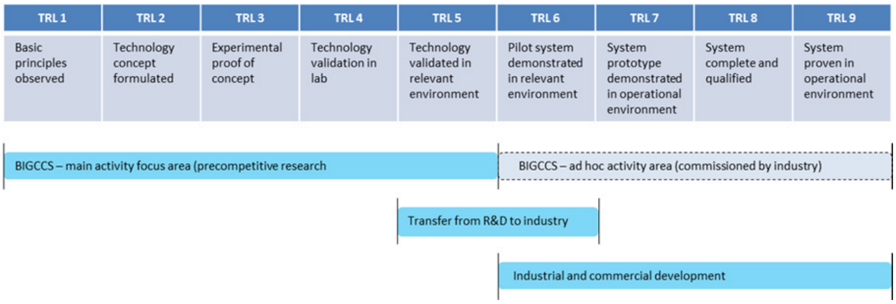

Fig.1. Technology readiness level scale used for classification of BIGCCS innovations as defined by the European Commission [40].

In order to classify the innovation status or progress of research activities, BIGCCS researchers have adopted a technology readiness level (TRL) scale (Fig. 1). The scale runs from TRL 1, which reflects a "basic principle observed", through TRL 9 reflecting a result ready for market implementation, or "proven in an operational environment". The use of this scale makes it easy for industrial partners to keep track of the development level of the different activities and prepares them to assume responsibility for the ultimate commercial development phase. Innovations are usually "owned" by BIGCCS researchers from TRL 1 to TRL 5, then transferred from R&D to the industry company at TRL 4 or TRL 5, while industry companies leads the commercial development from TRL 6 through TRL 9.

Following below, and summarized in Table 1, is a brief presentation of some of the most promising BIGCCS innovations.

Table 1. A selection of BIGCCS innovations with technology readiness level classification.

SP/Task	Innovation	TRL level
SP1/Task 1.1	CO_2 precipitation at process condition during operation	3
SP1/Task 1.2	Oxy-combustion with high temperature ceramic oxygen separation membranes	2
SP1/ Task 1.3	Analytic model for prediction of flashback in turbulent confined tubes	2
SP1/Task 1.4	Low emission, low penalty pre-combustion CO_2 capture with Exhaust Gas Recirculation (EGR)	1--2
SP1/Task 1.4	Burner for oxy-combustion gas turbine	2
SP1/Task 1.4	Oxy-fuel high pressure combustion rig	4--5
SP1/Task 1.4	EGR burner	3
SP1/Task 1.5	Low temperature CO_2 liquefaction and separation process primarily for use in pre-combustion capture	2
SP1/Task 1.5	A novel and elegant methodology for the design of post combustion capture membrane system	2
SP1/Task 1.6	Post combustion capture from the natural gas combined cycle (NGCC) with calcium looping	2
SP1/Task 1.3	Distributed fuel injection – a concept for environment-friendly and energy-efficient hydrogen combustion	2--3
SP1/Task 1.7	The 3 kW CLC test rig	4
SP1/Task 1.7	Powder production	5--6
SP2/Task 2.1	Coupled fluid-structure fracture-propagation control model	3--4
SP2/Task 2.2	CO_2Mix phase-equilibrium setup	4
SP2/Task 2.2	Gravitational preparation of calibration gas	4--6
SP3/Task 3.3	Methodology for CO_2 quantification	3
SP3/Task 3.4	Method for assessing thermal tensile strength of caprock	4
SP3/Task 3.5	Method for numerical prediction of well leakage	4
SP3/Task 3.2/3.6	Stability analysis for diffusion-driven convection	3
SP4/Task 4.1	Value chain methodology	2
SP4/Task 4.1	Integrated multi-criteria CCS chain assessment tool	2

2. CO_2 capture innovations

Technologies with higher efficiency and lower cost and foot print for CO_2 capture are essential for realization of CCS. Several innovative activities and ideas are developed through BIGCCS to support the capture technologies and fill the scientific gaps.

2.1 CO_2 precipitation at process condition during operation (TRL 3)

Absorbed CO_2 is precipitated as solid crystals early in absorption. Crystals formed dissolve readily at lower temperatures with CO_2 release thus enabling lower regeneration energy and high pressure CO_2 regeneration possibility, than the conventional amine technology. This technology will be of benefit to organizations that work towards reducing carbon footprint in the industries.

2.2 Oxy-combustion with high temperature ceramic oxygen separation membranes (TRL 2)

The concept is to fully integrate the air separation unit (ASU) and the oxy-combustion chamber into a dense ceramic membrane combustor as shown in Fig. 2. This concept has the potential of significant improvement in the heat integration of the membrane based ASU and improved catalytic flame-less combustion [3].

(a) (b)

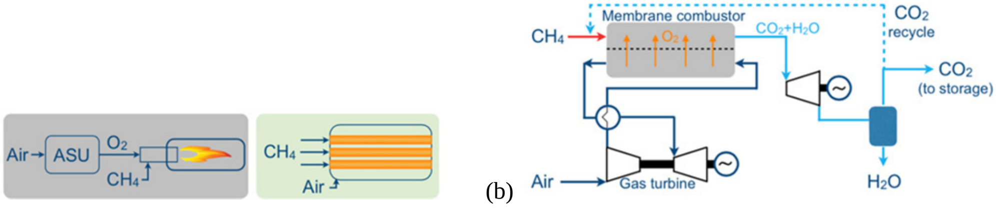

Fig. 2. (a) Oxy-fuel with ASU and conventional combustion chamber (left), and tubular membrane combustor with separate streams for fuel/air inlets and outlets (right); (b) Simplified process scheme for integration of membrane combustor with a standard gas turbine (air) and a CO_2/H_2O gas turbine.

2.3 Analytic model for prediction of flashback in turbulent confined tubes (TRL 2)

A new, analytic mean flame shape model, that considerably improves present state-of-the-art approaches for prediction of flashback in ducts, is developed and validated versus Direct Numerical Simulation datasets.

2.4 Low emission, low penalty pre-combustion CO_2 capture with exhaust gas recirculation (TRL 1-2)

The pre-combustion capture route is conditioned by the combustion of a high hydrogen content fuel (> 80%) which is a source of high NO_x emissions. To avoid the penalty associated with gas cleaning or immature hydrogen fired low NO_x burners, the concept of Exhaust Gas Recirculation applied to the hydrogen fired gas turbine has been proposed, inherently limiting the formation NO_x [4,5].

2.5 Burner for oxy-combustion gas turbine (TRL 3)

Oxy-combustion gas turbines are still not commercially available today [6]. The burner designed and tested in relevant pressure conditions in BIGCCS is a major component of such a gas turbine, thus bringing it closer to realization.

2.6 Oxy-fuel high pressure combustion rig (TRL 4-5)

HIPROX is an experimental rig that has been fully operative for the last two years, specifically designed to study oxy-fuel combustion in gas turbine conditions [7].

2.7 EGR burner (TRL 3)

To increase the CO_2 concentration in post-combustion plants and reduce capture plant energy consumption [8], exhaust gas recirculation (EGR) in the gas turbine has been studied. However, combustion in typical combustors with EGR becomes unstable, as oxygen is reduced. In this innovation a burner concept based on the

MILD combustion principle, was successfully tested for high EGR rates for pressures up to 10 bars, while avoiding combustion stability issues.

2.8 Low temperature CO_2 liquefaction and separation process for use in pre-combustion capture (TRL 2)

This technology has been indicated to be more energy- and cost-effective than baseline technology (physical solvents) [9,10]. The Low Temperature technology is more favorable for gases with high CO_2 concentration (35-45%), which is common for synthesis gases based on coal gasification. It is based on compression, cooling and phase separation, where the CO_2-rich liquid phase is purified in a secondary flash separator. Final pressurization is provided by liquid pumping of the CO_2. If liquid CO_2 for ship transport is required as product, this can be drained off directly from the secondary separator.

2.9 A novel and elegant methodology for the design of post combustion capture membrane system (TRL 2)

Experience from literature has shown that designing a process to minimize energy use alone is sub-optimal from a cost perspective. A visual tool has therefore been developed that makes the design of post-combustion membrane systems very simple and intuitive [11,12]. Cost is incorporated as part of the design process so the user can inherently consider the membrane area energy trade-off when making the design. Another key feature is that this visual tool provides feedback to membrane development.

2.10 Post combustion capture from the natural gas combined cycle (NGCC) with calcium looping (TRL 2)

A modern, large industrial gas turbine has an exhaust temperature of typically ~600°C, suitable temperature for Calcium Looping (CaL) technology. Process simulations for post-combustion capture from the Natural Gas Combined Cycle (NGCC) using Calcium Looping (CaL) in BIGCCS shows that the simplest process configuration did not give an efficiency superior to the NGCC with MEA capture [13]. However, adding a recuperator between the solids streams, improving steam data and adding hot recycle of CO_2, an improved Ca-sorbent and finally oxygen production with an oxygen transport membrane (OTM) yielded a process efficiency of 53.1%, which corresponds to a CO_2 capture penalty of only 5%-points [14].

2.11 Distributed fuel injection – concept, environment-friendly, energy-efficient hydrogen combustion (TRL 2-3)

A main hurdle for realizing hydrogen-fueled gas turbines, including the Integrated Gasification Combined Cycle (IGCC) with CO_2 capture, is the lack of gas turbines capable of burning hydrogen in an environmental-friendly, yet energy-efficient manner. Distributed Fuel Injection (DFI) is a concept that has been proposed in BIGCCS as a possible means to resolve the challenges associated with hydrogen combustion in gas turbines. With DFI, hydrogen is provided to the combustion air through a H_2-separating membrane or a porous wall. This could be a means of avoiding both concentrated fuel point sources and N_2 dilution of the fuel [15].

2.12 The 3 kW CLC test rig (TRL 4)

The 3 kW test rig is designed to test attrition properties of oxygen carrier particles in dual circulating hot CLC rigs. This unique test rig will give valuable information on material strength on realistic operating conditions.

2.13 Powder production (TRL 5-6)

Powder in small scale of 1-10 kg is produced, using equipment that it is possible to scale up. This innovation is important for Norwegian industry, institutes and university since it gives them the possibility to test production of new materials for different applications, while reducing their cost and risk compared to larger scale test facilities.

3. CO_2 transport innovations

Safe and cost-efficient CO_2 transport will be essential for full-scale CCS deployment. As part of the necessary considerations regarding safety, design and operation of pipelines, we must be able to perform accurate computations of various transient two-phase flow phenomena [19]. Similar considerations also apply for ship transport of CO_2. Fracture propagation control in pipelines is a subject in need of attention, since today's engineering tools are not adequate. Unlike the situation for natural gas, there currently exists no reference equation of state for CO_2-rich mixtures. Accurate property models for CO_2-rich mixtures are, however, a prerequisite for calculations regarding conditioning, transport or storage, including metering of the amount of CO_2 stored.

3.1 Coupled fluid-structure fracture-propagation control model (TRL 3-4)

Running-ductile fracture may be compared to what happens to a sausage if you boil it instead of simmering it: It will crack open. Transport pipelines, be it for natural gas or CO_2, should be designed so that a fracture will not propagate for a long distance. In the past, semi-empirical engineering tools, called two-curve methods, have been developed for safe design and operation of natural-gas pipelines. These tools are not made for newer, high-toughness steels, and particularly not for CO_2, whose properties are distinctly different from those of natural gas. Indeed, researchers working in the National Grid-led COOLTRANS project in the UK have clearly stated that the Battelle two-curve method cannot be directly applied to dense phase CO_2 pipelines [22]. The working hypothesis of BIGCCS Task 2.1 CO_2 pipeline integrity is that inclusion of more physics in the modelling will lead to greater predictive capability. This has led to a model which is internationally unique due to its combination of advanced fluid and material mechanics – including the two-phase decompression behaviour of CO_2 [18,21]. A feature of the model is the direct physical coupling between the fluid and the structure. The model has been validated for running-ductile fracture experiments in pipelines pressurized with methane and hydrogen, and good results were obtained [25]. However, available data for CO_2 pipelines are very scarce. The CO2Pipetrans II consortium, led by DNV-GL has provided access to data from two medium-scale crack-arrest experiments for pipelines pressurized with CO_2. The first results have been submitted [8]. If the work is successful, the model will be useful in situations where situations where operating conditions in existing pipelines are changed and fracture-propagation issues must be re-evaluated due to these changes, or during the design phase of a new pipeline where fracture-propagation control issues must be addressed.

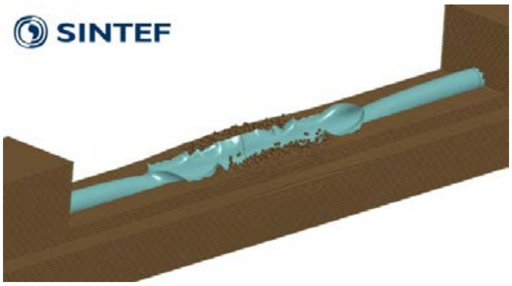

Fig. 3. Coupled fluid-structure simulation of running-ductile fracture in a CO_2 pipeline. Such simulations will help design safe and cost-effective CO_2-transport networks [17].

3.2 CO2Mix phase-equilibrium setup (TRL 4)

There are still large gaps in the experimental data of thermophysical properties of CO_2-rich mixtures relevant for CCS [20,23,24]. Data from phase equilibria measurements are one of the types of data required for the development of accurate equations of state. Thus in the CO2Mix project, part of the CO_2-transport sub-program in BIGCCS, a highly accurate phase-equilibrium setup has been developed [26], and unique data are currently being acquired [27]. The data can and should be used to develop new or improve existing predictive models for thermophysical properties.

3.3 Gravitational preparation of calibration gas (TRL 4-6)

For phase-equilibrium measurements (above), gas-mixtures of very accurate composition are required. Such mixtures are not commercially available. Therefore, a setup using a gravimetrical technique has been developed, enabling the preparation of gases with an accuracy in composition of the order of 1 ppm in a 10 liter gas cylinder. The setup is general in nature and technique be used for a range of different fluids and quantities.

4. CO_2 storage innovations

The ability to cost-efficient and safe injection of large amounts of CO_2 as well as documenting the long-term containment is essential for deployment of CCS at a scale relevant for limiting global CO_2 emissions. A main focus in BIGCCS research on CO_2 storage is to develop methods and technology to maximize storage integrity and minimize uncertainty. In the following, four examples of innovations that contribute to providing such measures are presented.

4.1 Methodology for CO_2 quantification (TRL 3)

By combining complementary geophysical methods like Controlled Source Electro-Magnetics (CSEM) and Full Waveform Inversion (FWI), the full potential of available data can be used to obtain more sensitive and accurate monitoring strategies. A new combined methodology for CO_2 quantification has been developed and tested on data obtained from a synthetic Sleipner model. The results when estimating CO_2 volume are promising [28]. If the technology is successfully demonstrated in a relevant environment using real data collected at Sleipner, it will become an important tool for monitoring of CO_2 storage, with both storage operators and service companies being potential users. In particular the capability to detect leakage and quantify CO_2 volumes will be improved.

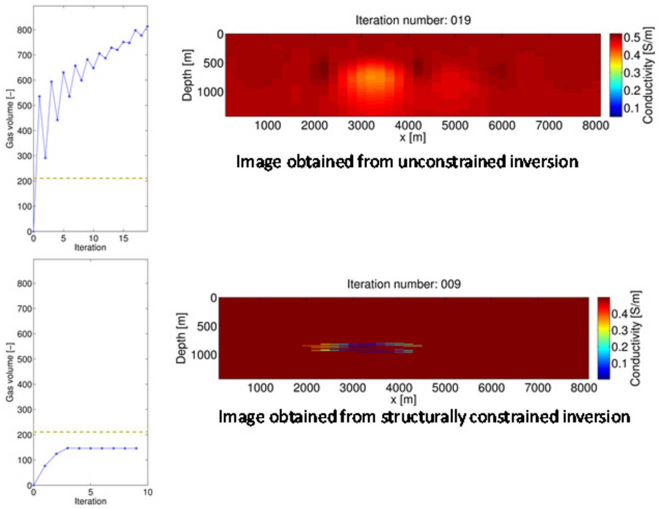

Fig. 4. Volume estimate and conductivity model obtained when using unconstrained CSEM inversion (top). Volume estimate and conductivity model obtained when using CSEM inversion constrained by structural information assumed to be derived from seismic inversion (bottom). The dotted line indicates the true gas volume (both).

4.2 Method for assessing thermal tensile strength of caprock (TRL 4)

CO_2 flowing down an injection well will often be colder than the surrounding formations. This is especially true in ship transport schemes, where heating expenses at the wellhead will be kept minimal. The lower temperature in the well will cause the casing to contract. Contrasting mechanical and thermal properties of casing, cement and shale may lead to tensile thermal stresses appearing in the shale. Since shale tensile strength is low, it may crack. If cracks propagate to the next permeable layer, leakage may occur. In BIGCCS an adaptation of the simple Brazilian indirect tensile test is developed to measure thermal tensile stress development in caprock samples to assess thermal fracturing risk and give guidelines on safe temperature ranges for CO_2 injection wells. This set up uses infra-red lamps to heat a shale disc under no-deformation conditions, building up tensile thermal stress in the specimen [29,30].

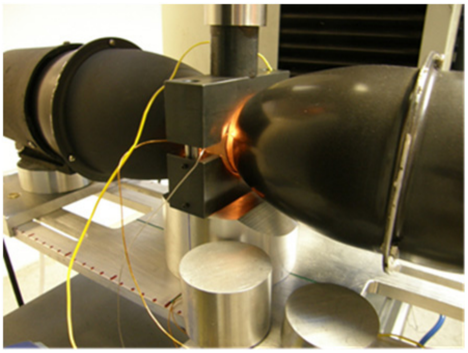

Fig. 5. The method can be used as a routine test in the approval of selected storage sites in terms of injection plan, so as to ensure safe storage with minimum leakage risk. The user of the innovation would be either storage permit holders or perhaps preferably accredited laboratories in charge of site approval for the regulatory authorities.

4.3 Method for numerical prediction of well leakage (TRL 4)

Well integrity depends heavily on how the materials of the well bond with each other, e.g. bonding between casing and cement and between cement and rock. In BIGCCS a method for calculating leakage through wells is developed using micro CT (computed tomography) for making digital 3D representation of leakage paths. The method is used for reconstructing leakage paths in the bonding between cement and rock in cement-shale plugs and the results are validated against measurements of flow through the plugs. This method could form the basis of a software tool (e.g. a "Leakage predictor") that operators and service companies could use to calculate the probability of leakage through wells based on various known input parameters (cement type, mud type, rock type, well operation history) [31,32].

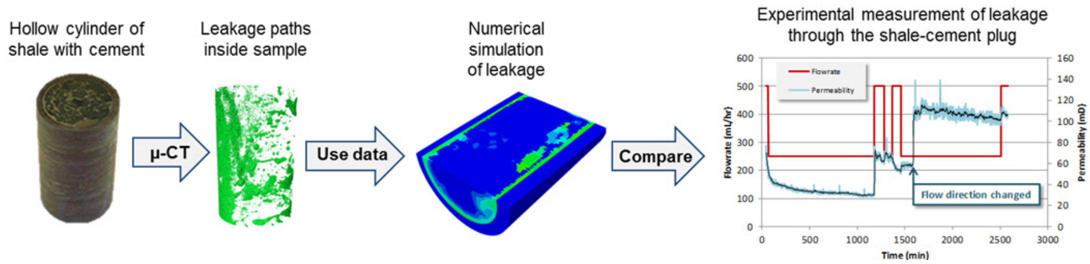

Fig. 6. The developed method includes three steps: 1) Tomography to digitalize pores/voids in downscaled well samples. These can (if connected) form leakage paths in wells. 2) Reconstruct the tomography data in three dimensions (3D) and extract the coordinates of pore volumes 3) Transfer the digital pore volumes to software capable of calculating flow/leakage (e.g. ABAQUS). The results are compared with experimental measurements.

4.4 Stability analysis for diffusion-driven convection (TRL3)

Improved knowledge on convection as an enhancer for the dissolution trapping mechanism has been the objective of a long-term theoretical work in BIGCCS. Dissolution of CO_2 in water will cause gravitational instability of the aquifer underneath the CO_2 gas cap. Density currents of brine with dissolved CO_2 will speed up dissolution of CO_2 and thereby the transition to permanent containment. The phenomenon is difficult to analyze with mathematical models and few have taken on the challenge of proving the theoretical basis. In BIGCCS, the minimal time for onset of instability is investigated [33,34]. Underpinning experimental and numerical work is conducted [35,36,37].

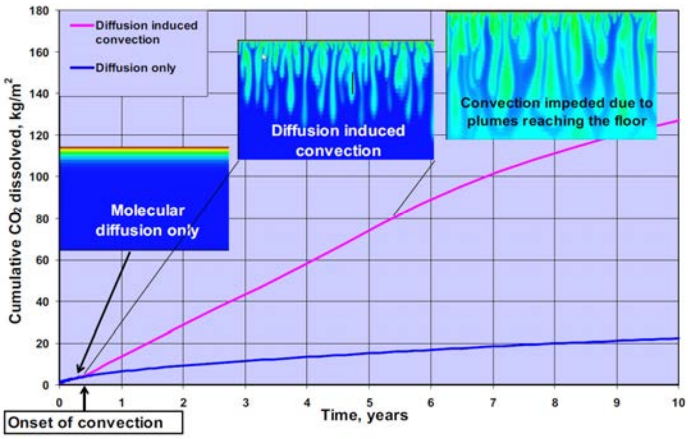

Fig. 7. Cumulative dissolved CO_2 derived from a numerical flow simulation. The dissolution of CO_2 resulting from pure diffusion is (i.e. the basic solution) is significantly less compared to the dissolution resulting from the convective mixing.

The stability analysis for diffusion-driven convection in aquifers with CO_2 storage improves the theoretical basis for understanding storage safety on the long term, and enables improved estimates of the time scale related to onset of the convection. This is important for the evaluation and selection of storage sites as it can be used to check the accuracy of numerical simulations that consider diffusion-driven convection.

5. CO_2 value chain innovations

5.1 Value chain methodology (TRL 2)

To bring CCS closer to commercial realization, the viability of CCS projects must be explored, including technological, economic, and environmental effects. A consistent and transparent methodology that allows critical evaluation of a CCS chain with respect to multiple criteria was developed in BIGCCS SP4 [38,39]. The methodology enables fair comparison of various CCS projects based on integrated assessment of techno-economic and environmental impacts while also taking into account the economic, societal, and political environment of the CCS chain. The methodology is designed to deal with the wide range of various actors and aspects involved in CCS in an appropriate manner by applying relevant methods and tools. While the quantitative variables and parameters are treated by use of mathematical models, the non-quantifiable variables such as political incentives and regulations are investigated with help of methodologies aimed at soft-data handling. The toolbox consists of three main parts: scenario development methodology, case study methodology, and simulation tool for quantification of Key Performance Indicators (KPIs) the iCCS tool (see below).

The value of this methodology lies predominantly in the support it provides to decision-makers in selecting the best alternatives for CCS chains. The methodology will help to provide additional knowledge for the design of efficient CCS chains, and identify efficient policy tools and measures to promote the development of CCS.

5.2 Integrated multi-criteria CCS chain assessment tool (TRL 2)

The integrated multi-criteria CCS chain assessment tool (iCCS) was developed by SINTEF ER in BIGCCS SP4 based on the above mentioned methodology. The iCCS tool provides support for technology selection as well as smart design and operation of CCS chains. The iCCS tool has a modular structure to ensure flexibility, as shown in Fig. 8. A library of modules is being developed to model the chain components: capture, conditioning, transport, and storage. These modules can be used as basic building blocks and interconnected freely to create a range of potential chain designs. This feature enables users to simulate a large number of CCS chains in a consistent manner. The tool allows for evaluation of KPIs (important technical, economic, environmental criteria) on several levels: chain component, actor or owner of components, and the overall chain. Typical KPIs for the CCS chain evaluation are for example: Net Present Value (NPV), electricity production cost, the cost of CO_2 avoided. The tool is especially suitable for parameter sensitivity studies. New modules and additional assessment criteria can be easily added within this modular framework.

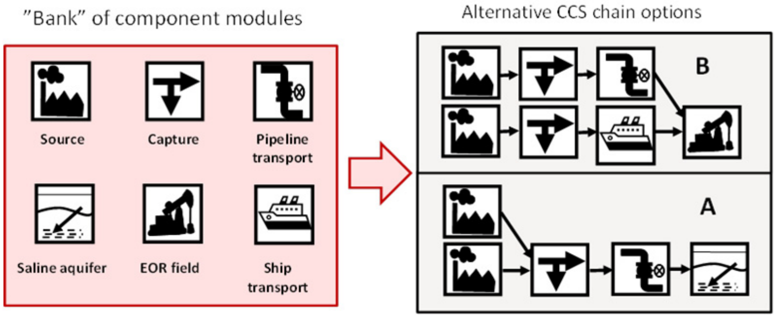

Fig. 8. Illustration of the modular structure of the iCCS tool

The comprehensive and consistent methodology and the iCCS tool developed under SP4 are of particular interest for:

- Potential CCS infrastructure owners and or customers as it enables selecting the most cost-effective options for CCS deployment;
- Technology providers and engineering companies as it will highlight the needs for technology improvements and measures to promote the CCS technology;
- Policy and decision makers as the tool could be used to assess the effects of alternative policy and global market scenarios on the CCS chain economy.

6. Summary and Conclusions

The focus on innovation opportunities has been held high throughout the entire period of BIGCCS. As technology development has progressed and technologies have matured, the emphasis on bringing useful results to the BIGCCS industry partners has increased. This paper has presented some 22 of the most promising innovations from BIGCCS, all with a potential of giving benefits to industry companies, either inside or outside BIGCCS. During the remaining period of the BIGCCS Centre, activities will focus on validation of results and innovations, and on transferring innovation ownership to the industrial partners. The ultimate goal is commercialization of products and processes that can stimulate deployment of CCS technologies to the market.

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References

[1] www.bigccs.no

[2] http://www.forskningsradet.no/prognett-energisenter/Home_page/1222932140849

[3] Sundkvist, S.G., Julsrud, S., Vigeland, B., Naas, T., Budd, M., Leistner, H., Winkler, D. *Development and testing of AZEP reactor components*. Int. J. Greenh. Gas Control. 1, 180–187, 2007.

[4] Ditaranto, M., Li, H., Hu, Y. *Evaluation of a pre-combustion capture cycle based on hydrogen fired gas turbine with exhaust gas recirculation (EGR).* Energy Procedia 63: 1972-1975, 2014.

[5] Ditaranto, M., Li, H., Løvås, T. *Concept of hydrogen fired gas turbine cycle with exhaust gas recirculation: Assessment of combustion and emissions performance.* ii37:377-383, 2015.

[6] Sundkvist, S.G., Dahlquist, A., Janczewski, J., Sjödin, M., Bysveen, M., Ditaranto, M., Langørgen, Ø., Seljeskog, M., Siljan, M. *Concept for a Combustion System in Oxyfuel Gas Turbine Combined Cycles.* Journal of Engineering for Gas Turbines and Power 136(10):101513-101513-10, 2014.

[7] Ditaranto, M. *Description of a high pressure oxy-fuel combustion facility HIPROX*. 2nd Oxyfuel Combustion Conference, Yeppoon, Australia. 12-16 September 2011.

[8] Lindqvist, K. Jordal, K., Haugen, G., Hoff, K.A., Anantharaman, R. *Integration aspects of reactive absorption for post-combustion CO_2 capture from NGCC (natural gas combined cycle) power plants*. Energy 78 (2014) 758-767.

[9] Berstad, D., Anantharaman, R., Nekså, P. *Low-temperature CCS from an IGCC Power Plant and Comparison with Physical Solvents*. Energy Procedia 37 (2013) 2204-2211.

[10] Berstad, D., Roussanaly, S., Skaugen, G., Anantharaman, R., Nekså, P., Jordal, K. *Energy and Cost Evaluation of A Low-temperature CO2 Capture Unit for IGCC plants*. Energy Procedia 63 (2014) 2031-2036.

[11] Lindqvist, K., Roussanaly, S., Anantharaman, R. *Multi-stage Membrane Processes for CO_2 Capture from Cement Industry*. Energy Procedia 63 (2014) 6476-6483.

[12] Roussanaly, S., Lindqvist, K., Anantharaman, R., Jakobsen, J. *A Systematic Method for Membrane CO2 Capture Modeling and Analysis.* Energy Procedia 63 (2014) 217-264.

[13] Berstad, D., Anantharaman, R., Jordal, K., *Post-combustion CO_2 capture from a natural gas combined cycle by $CaO/CaCO_3$ looping*, International Journal of Greenhouse Gas Control 11 (2012), 25-33.

[14] Berstad, D., Anantharaman, R., Blom, R., Jordal, K., Arstad, B. *NGCC post-combustion CO2 capture with Ca/carbonate looping: Efficiency dependency on sorbent properties, capture unit performance and process configuration*. International Journal of Greenhouse Gas Control 24(2014) 43-53.

[15] Jordal, K., Anantharaman, R., Gruber, A., Peters, T., Henriksen, P.P., Berstad, D., Bredesen, R. Performance of the IGCC with distributed feeding of H_2 in the gas turbine burner. Energy Procedia 63 (2014) 2037-2044.

[16] Aursand, E., Dumoulin, S., Hammer, M., Lange, H.I., Morin, A., Munkejord, S.T., Nordhagen, H.O. *Fracture propagation control in CO_2 pipelines. Validation of a coupled fluid-structure model*. Submitted. 2015a.

[17] Aursand, E., Dumoulin, S., Hammer, Munkejord, S.T., Nordhagen, H.O. *Simulating running ductile fracture in CO_2 pipelines*. SINTEF Energy blog. 16 June, 2015b.

[18] Aursand, E., Dørum, C., Hammer, M., Morin, A., Munkejord, S.T., Nordhagen, H.O. *CO_2 pipeline integrity: Comparison of a coupled fluid-structure model and uncoupled two-curve methods.* Energy Procedia 51, 382–391, 2014.

[19] Aursand, P., Hammer, M., Munkejord, S.T., Wilhelmsen, Ø. *Pipeline transport of CO_2 mixtures: Models for transient simulation.* Int. J. Greenh. Gas Con. 15, 587 174–185, 2013.

[20] Gernert, G.J. *A new Helmholtz energy model for humid gases and CCS mixtures.* PhD thesis, Faktultät für Maschinenbau, Ruhr-Universität Bochum. 2013.

[21] Hammer, M., Ervik, Å., Munkejord, S.T. *Method using a density-energy state function with a reference equation of state for fluid-dynamics simulation of vapour-liquid-solid carbon dioxide.* Ind. Eng. Chem. Res. 52 (29), 9965–9978, 2013.

[22] Jones, D.G., Cosham, A., Armstrong, K., Barnett, J., Cooper, R. *Fracture-propagation control in dense-phase CO_2 pipelines.* 6th International Pipeline Technology Conference. Ostend, Belgium, paper no. S06-02, 2013.

[23] Li, H., Jakobsen, J.P., Wilhelmsen, Ø., Yan, J. *PVTxy properties of CO_2 mixtures relevant for CO_2 capture, transport and storage: Review of available experimental data and theoretical models.* Appl. Energ. 88, 3567–3579, 2011.

[24] Li, H., Wilhelmsen, Ø., Lv, Y., Wang, W., Yan, J. *Viscosities, thermal conductivities and diffusion coefficients of CO_2 mixtures: Review of experimental data and theoretical models.* Int. J. Greenh. Gas Con. 5, 1119–1139, 2011.

[25] Nordhagen, H.O., Kragset, S., Berstad, T., Morin, A., Dørum, C., Munkejord, S.T. *A new coupled fluid-structure modelling methodology for running ductile fracture.* Comput. Struct. 94–95, 13–21, 2012.

[26] Stang, H.G.J., Løvseth, S.W., Størset, S.Ø., Malvik, B., Rekstad, H. Accurate measurements of CO_2-rich mixture phase equilibria relevant for CCS transport and conditioning, Energy Procedia 37, 2897–2903, 2013.

[27] Westman, S.F., Stang, H.G.J., Løvseth, S.W., Austegard, A., Snustad, I., Størset, S.Ø., Ertesvåg, I.S. *Vapor-liquid equilibrium data for the carbon dioxide and nitrogen (CO_2+N_2) system at the temperatures 223, 270, 298 and 303 K and pressures up to 18 MPa.* Fluid Phase Equlib. In press, 2015.

[28] Eliasson, P., Romdhane, A., Jordan, M., Queren, E. *A synthetic Sleipner study of CO_2 quantification using controlled source electromagnetics and full waveform inversion*. Energy Procedia, Volume 63, Pages 4249–4263, 2014.

[29] Cerasi, P., Stroisz, A.M., Walle, L.E., and Lavrov, A. *Laboratory testing of shale rock specimens to assess thermal fracturing risk in caprock surrounding injection wells.* ARMA 14-7077. The 48th US Rock Mechanics/Geomechanics Symposium, Minneapolis, MN, USA. 1-4 June, 2014.

[30] Cerasi, P., Stroisz, A.M., Walle, L.E., and Lavrov, A. *Numerical modeling of tensile thermal stresses in rock around a cased well caused by injection of a cold fluid.* ARMA 13-306, The 47th US Rock Mechanics/Geomechanics Symposium held in San Francisco, CA, USA. 23-26 June, 2013.

[31] Opedal, NvdT, Torsæter, M., Vrålstad, T., Cerasi, P. *Potential leakage paths along cement-formation interfaces in wellbores; Implications for CO_2 storage*. Energy Procedia 2014 (51) 56-64.

[32] Lavrov A., Torsæter, M., Albawi, A., Todorovic, J., Opedal, N., Cerasi, P. *Near-well integrity and thermal effects: a computational road from laboratory to field scale ARMA 14-7109.* The 48th US Rock Mechanics/Geomechanics Symposium, Minneapolis, USA, 1-4 June 2014.

[33] Taheri, A.; Wessel-Berg, D.; Torsæter, O. *Simulation study of density-driven natural convection mechanism in isotropic and anisotropic brine aquifers using a black oil reservoir simulator*. Energy Procedia 2013 (37) 5562–5569, 2013.

[34] Wessel-Berg, D. *The gravitational instability of a diffusive boundary layer; towards a theoretical minimum for time of onset of convection*. ECMOR XIII, Biarritz, France, 10-13 September, 2012.

[35] Soroush, M. *Simulation and Experimental Investigation of Different Phenomena in CO_2 Storage in the Saline Aquifers*. NTNU PhD thesis. ISBN 978-82-326-0194-3, 2014.

[36] Taheri, A. *Experimental and Numerical Study of Density-Driven Natural Convection Mechanism during Storage of CO_2 in brine aquifers*. NTNU PhD thesis. 2015.

[37] Lindeberg, E., Wessel-Berg, D. *Upscaling studies of diffusion induced convection in homogeneous and heterogeneous aquifers*, Energy Procedia 2011 (4), 3927-3934, 2011.

[38] Jakobsen, J.P., Brunsvold, A., Husebye, J., Hognes, E.S., Myhrvold, T., Friis-Hansen, P., et al. *Comprehensive assessment of CCS chains-Consistent and transparent methodology*. Energy Procedia. 2011;4:2377-84.

[39] Jakobsen, J.P., Roussanaly, S., Mølnvik, M.J., Tangen, G. *A standardized approach to multi-criteria assessment of CCS chains*. Energy Procedia. 2013;37:2765-74.

[40] "Technology readiness levels (TRL)" (PDF). European Commission, G. Technology readiness levels (TRL), HORIZON 2020 – WORK PROGRAMME 2014-2015 General Annexes, Extract from Part 19 - Commission Decision C(2014)4995.