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A tool for integrated multi-criteria assessment of the CCS value chain

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Abstract

BIGCCS Centre is an international research center aiming at extending and releasing the potential for large scale deployment of CO_2 capture and storage. A consistent and transparent methodology and tool, called iCCS, was developed in BIGCCS SP4 as one of the measures aimed at bringing CCS closer to commercial realization. iCCS allows critical evaluation of CCS chains with respect to multiple techno-economic and environmental criteria. The tool has modular structure and enables the user to build different CCS chain configurations from capture, transport and storage modules available in the tool library. This makes it possible to simulate a large number of CCS chains and to compare them in a consistent manner.

The philosophy of this methodology and the tool developed are presented in this work and is illustrated through case studies; for example to compare different capture, transport or storage cases, as well as for a full chain analysis. This paper presents a list of case studies performed under the BIGCCS framework and brings together the results of three latest studies. Two of these studies focus on comparison of technologies for CO_2 capture from a) an Integrated Gasification Combined Cycle, and b) a coal fired power plant and a cement plant. The third case study looks at valuation of CO_2 for Enhanced Oil Recovery.

The presented case studies illustrate how the methodology and tool could be used to provide support for technology selection. Additionally, the tool allows smart design and operation of CCS chains and thereby enables selection of most suitable CCS chain configurations for specific cases with respect to techno-economic and environmental impacts.

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Keywords: Carbon Capture and Storage; CCS; techno-economic assessment; low-temperature capture; membrane CO_2 capture, CO_2 EOR.

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1. Introduction

The rate of greenhouse gas emissions is further accelerating with the growth of gross domestic product and population despite all the reduction efforts. The climate change mitigation requires major technological and institutional changes throughout all sectors of the economy. Delaying the mitigation actions is estimated to increase the difficulty and narrow the options for limiting the global warming to 2°C [1]. If we are to keep global temperature increases below 2°C, CCS is essential as it is a vital part of least cost portfolio of low-carbon technologies required to deal with climate change. However, despite significant progress within CCS technologies the momentum for further development and deployment of CCS is slowing down especially in Europe [2].

BIGCCS Centre is an international research centre aiming at extending and releasing the potential for large scale deployment of CO_2 capture and storage by developing new knowledge, fostering breakthrough technology and promoting innovation and future value creation at all steps along the CO_2 chain. The centre is managed by SINTEF Energy Research (SINTEF ER) and engages 22 partners from industry and academia over a time period of 8 years [3]. BIGCCS has increased the yearly budget from 40 million NOK in 2009 to 70 million NOK in 2012 due to inclusion of four competence building projects, and additional research infrastructure investments [4]. BIGCCS is organized in five Sub-Projects (SPs): SP1 CO_2 capture, SP2 CO_2 transport, SP3 CO_2 storage, SP4 CO_2 value chain, and SP5Academia. While the sub-programs 1-3 of the BIGCCS Research Centre investigate particular technologies and aim at their improvement, in Sub-Program 4 "CO_2 value chain" the value chain methodology and tool for multi-criteria assessment of CCS chains is being developed.

2. Methodology

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 [5, 6]. 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). Typical KPIs for the CCS chain evaluation are for example: Net Present Value (NPV), electricity production cost, the cost of CO_2 avoided. 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.

3. Integrated multi-criteria CCS chain assessment tool

An 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 Figure 1. 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. The tool is especially suitable for parameter sensitivity studies. New modules and additional assessment criteria can be easily added within this modular framework.

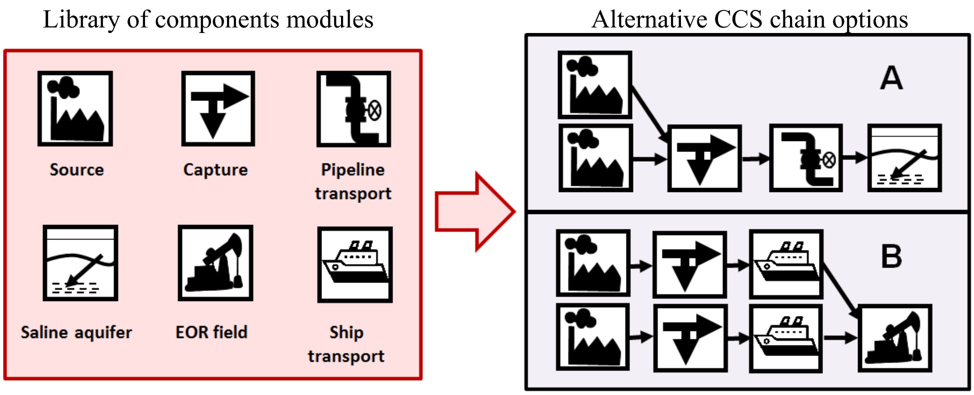

Figure 1: Illustration of the modular structure of the iCCS tool

The quantitative analysis of CCS chain KPIs with the tool follows six basic steps: I.CCS chain design; II. Specification of global parameters; III. Specification of component specific parameters; IV. Modeling of chain components, which means evaluation of KPIs on component level; V. Performing the overall analysis by evaluating key performance indicators for the whole chain; and VI. Representing the results as spider diagrams including all KPIs and/or aggregating KPIs into overall reporting measures (NPV, CO_2 captured, CO_2 avoided). The component models applied in step IV are parameterized meta-models for evaluation of KPIs based functions of input variables and parameters. The functions are derived from results obtained by more detailed technical modeling of the CCS chain components. Choice of appropriate parameters and the level of detail of the modeling work are of most importance.

The integrated techno-economic and environmental assessment on the component level could be summarized as follows. First, the technical assessment is performed based on modeling in Aspen Plus®, Aspen HYSYS®, or data available in the open literature. Then the cost assessment is performed based on sizing of equipment and utility consumption derived from the mass and energy balances obtained in the first step. The costing is done based on Aspen Process Economic Analyzer®, literature, cost factors, O&M, and utility costs. Finally, the GHG assessment is performed by means of a hybrid LCA method by use of Ecoinvent and IO Carnegie Mellon University databases. See the illustration of the approach in Figure 2.

While the module library is under continuous development,

Table 1 provides an overview of modules already implemented in the tool.

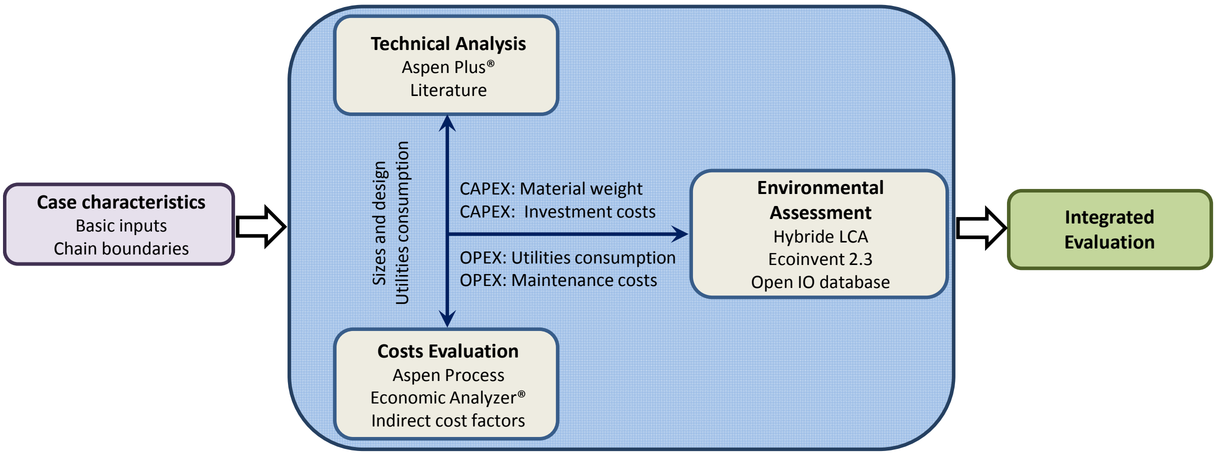

Figure 2: The integrated techno-economic and environmental assessment

Table 1: Module library - development status

Capture modules	Conditioning modules	Transport modules	Storage modules
1) Post-combustion MEA CO_2 capture	1) For pipeline export (on-shore/offshore	1) Onshore pipeline	1) Depleted Oil and Gas Fields
2) Post-combustion membrane CO_2 capture	2) For ship export (on-shore/offshore	2) Offshore pipeline	2) Saline Aquifers
3) CO_2 capture by liquefaction		3) Shipping between onshore harbours	3) EOR CO_2 Storage
		4) Shipping to offshore storage	

4. Case studies

Case study is an in-depth investigation that explores causation and governing underlying principles of the problem at hand. Case study, as a research method, shall be carefully designed, planned and crafted in order to study a particular situation, issue or problem and provide insight on the key issues related to CCS chain realization.

To cut the cost of CCS, two main ways can be investigated: 1) Technology improvement on the chain component level (e.g. improved design, use of novel materials) and 2) Smart design and operation of CCS chains. In order to reduce the cost of a CCS project, it is important to assess the cost reduction potential of both technology selection and smart design and operations of CCS chains. This could be done by means of a value chain analysis. The methodology and tool developed for value chain analysis in BIGCCS have been used and illustrated through several cases studies: for example to benchmark pipeline and shipping transport [7, 8], evaluation of CO_2 liquefaction capture and hybrid membrane/liquefaction capture technologies [9-12], investigation of the potential impact of process optimization via flexible amine capture [13] and optimal installed capacity [14] as well as for other applications [15].

This work brings together the results of various case studies performed under the BIGCCS framework. Overview of case studies with references to earlier publications is provided in Table 2. Three of the latest case studies performed with the methodology and the simulation tool described in this paper are briefly presented in the following sections. The full description of the cases and more detailed discussion of the results are to be found in the referred papers directly devoted to each case study.

Table 2: Case studies performed under the BIGCCS value chain framework

Case study topic	References
Impact of CO_2 concentration on capture costs	[15, 16]
Optimal CO_2 capture plant capacity for fluctuating CO_2 emissions and flexible solvent regeneration	[13, 14]
Method for improved system design	[17-20]
Effects of the choice of capture technology on the costs	[9, 10, 12, 18, 19]
Transport technology selection and associated issues	[7, 8, 21]
Effects of the choice of storage type and EOR valuation issues	[10, 22]

4.1. Comparison of two technologies for CO_2 capture from an Integrated Gasification Combined Cycle (IGCC) [9, 10]

This work focused on the full techno-economic comparison of CO_2 capture, transport and storage from an IGCC power plant using CO_2 liquefaction capture or Selexol by comparing five power plant configurations without or with CCS chains based on the combination of the two capture technologies (liquefaction and Selexol) and two CO_2 transport options (pipeline and shipping) going to an offshore depleted oil and gas field for storage. As the CO_2 transport distance is an important parameter for the transport and overall chain costs, the comparison included the transport distance as a variable for the costs.

The assessment shows that the levelized cost of electricity (LCOE) including the full CCS chain and using the low-temperature technology ranges between 88 and 100 €/MWh for distances between 0 and 1000 km and is therefore in average 9% cheaper than with the Selexol technology. The full electricity cost using the low-temperature capture is in average 50% more expensive than in the case of an IGCC without CCS when no CO_2 emission penalty costs is considered. Regarding the CO_2 avoided cost, the assessment shows that the CCS chain using the low-temperature technology lead to costs ranging between 35 and 57 €/$t_{CO2,avoided}$ for distances between 0 and 1000 km and is therefore in average 23% cheaper than when using the Selexol technology.

The assessment also shows the importance of the CCS chain using CO_2 ship transport for moderate and large distances (above 225 km) as it can significantly decrease both electricity and CO_2 avoided costs compared to chains using CO_2 pipeline transport. Indeed, CCS with low-temperature capture remains below 55€/$t_{CO2,avoided}$ for distances shorter than 750 km which can also enable cost efficient capture, transport and storage even when no offshore CO_2 storage is available close to the IGCC power plant.

Additionally, the assessment highlights interesting synergies between the low-temperature capture and the shipping transport due to low costs, its limited environmental and health impacts. The low investment in the full chain also decreases the financial risks associated with implementation of CCS.

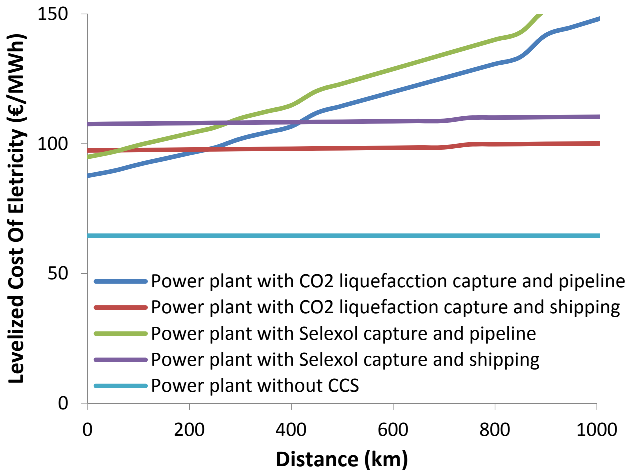

Figure 3: LCOE of the power plant with and without CCS chains in function of the CO_2 transport distance

4.2. Comparison of membrane CO_2 capture and MEA solvent capture for a coal fired power plant and a cement plant [17-19]

Gas separation membranes are considered among one of the promising technologies for post-combustion capture and has been studied extensively. With the limitations in existing membrane properties (selectivity and permeability) and other limitations, a single stage membrane process is not feasible to ensure CO_2 purity of 95% and CO_2 capture rate of 90% in the case of post-combustion capture. This results in complicated membrane configurations where numerous design decisions (process configuration, operation conditions and membrane properties) are required to ensure suitable driving force while minimizing work requirement and membrane area.

The literature [23] on process design for post-combustion capture using membranes involves studies where membrane properties and the process configuration is fixed and sensitivity studies are performed on operating conditions to "optimize" the process and then evaluate the cost of this "optimized" system. However similarly to pipeline systems for transport of gases [7, 8], two competing effects take place in the design of CO_2 membrane capture systems: high membrane investment cost for large membrane areas and significant process energy consumption for low membrane areas. Therefore the optimal design of a membrane system should be based on a systematic cost-based engineering optimisation.

A graphical methodology for systematic and consistent design of membrane processes for post-combustion capture has previously been developed at SINTEF Energy Research as part of BIGCCS [17]. An *attainable region* diagram is used to visualize the possible operating window of each membrane stage in addition to its optimal operating region. The number of stages and operating points are then easily identified using a step-wise approach similar to the McCabe Thiele diagram. As stated earlier, the methodology relies on robust engineering and cost models. A new and advanced cost model for membrane systems was developed to improve the accuracy of the economic evaluation and ensure consistent comparison with other technologies.

The methodology has been applied to a coal fired power plant [18] and a cement plant [19] to design membrane systems for post-combustion capture. The methodology resulted in simple stage-wise designs that resulted in lower costs than those in literature and were competitive compared to the "standard" Monethanolamine (MEA) post-combustion capture process. This can be mainly attributed to including cost as part of the design process and use of the intuitive and simple graphical design methodology developed.

4.3. The economic value of CO_2 for EOR applications [22]

While most works on CCS in connection with CO_2 EOR credit all the benefit of the additional oil production to the CCS entity, this work investigated the impact of alternative EOR methods on the valuation on CO_2 EOR storage. Based on a generic model suitable for CO_2 EOR in Norwegian oil fields, EOR productions with CO_2 injection is compared to the EOR production with chemical EOR for different scenarios.

The comparison shows that depending on the scenario combination considered, the added value of using the CO_2 EOR method instead of the chemical EOR method varies from -4 to 33 €/bbl$_{produced}$ equivalent to -4 to 56 €/t$CO_{2,avoided}$. In most of the cases considered, the CO_2 EOR method would therefore be preferred. The value creation however would vary depending on the case. The evaluation shows that for an oil price minus the normal production costs equal to 50 €/bbl, the oil value which shall be considered for CO_2 EOR application varies between 8 and 41 €/bbl, as shown in Figure 4. This can therefore be significantly lower than the 50 €/bbl which will be considered if chemical EOR is not an alternative.

In addition, the value one would be willing to pay to have CO_2 delivered at its field varies between -4 and 56 €/t$_{CO2}$ depending on the scenario combinations considered and can therefore also be significantly lower than in cases in which chemical EOR is not an alternative. For example, in the medium CO_2 EOR scenario, the CO_2 value is between 27 and 60% lower if chemical EOR is considered as an alternative option for EOR as shown in Figure 4.

The work therefore demonstrated that a CCS chain including CO_2 EOR would overestimate its benefits if it does not considered other EOR techniques as an alternative to CO_2 EOR for Oil & Gas companies. While specific cases would be required to obtain more accurate results, these results provide support to help to identify the range of costs which could be expected for CCS chains with EOR and therefore also the range of the emission penalty cost (CO_2 quota or tax) which would be necessary to make these chains viable. Indeed by crediting all the benefits of the additional oil production to the CCS entity, the emission penalty required is underestimated, therefore potentially giving the wrong indications to policy makers, CCS actors, as well as researchers on the correct value of CO_2 for EOR applications.

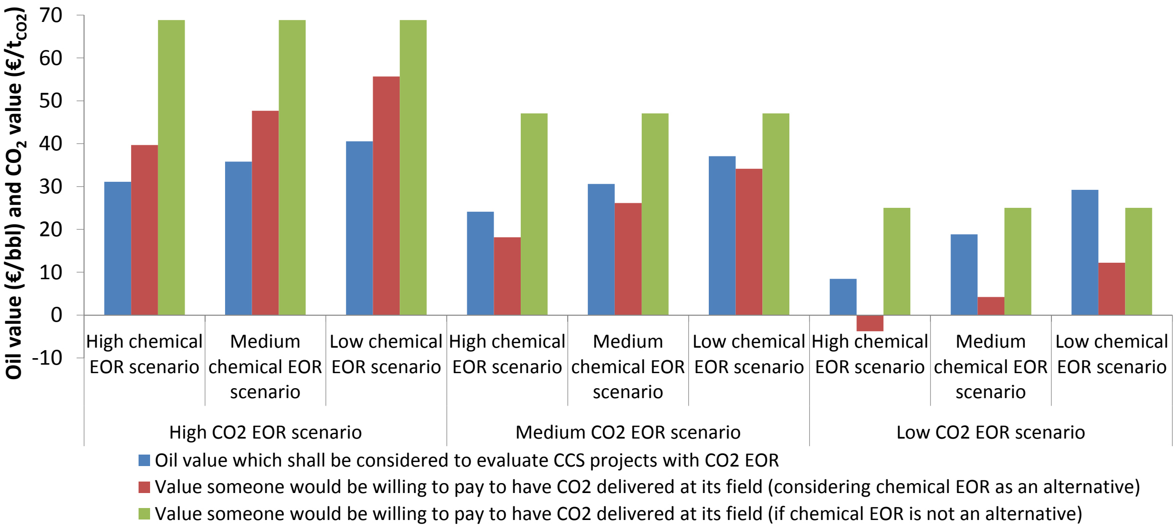

Figure 4: Oil values which shall be considered in CCS project associated with CO_2 EOR (€/bbl) and values one would be willing to pay for CO_2 delivered at its field (€/t$_{CO2}$)

5. Conclusions

A consistent and transparent methodology and simulation tool, called iCCS, for multi-criteria CCS chain assessment was developed within BIGCCS SP4. iCCS allows critical evaluation of CCS chains with respect to multiple techno-economic and environmental criteria. The tool has modular structure and enables the user to build different CCS chain configurations from capture, transport and storage modules available in the tool library. This makes it possible to simulate a large number of CCS chains and to compare them in a consistent manner.

The methodology and tool have been used to perform different types of case studies in order to illustrate their applicability. This paper focused on illustrating the tool functionalities and presents an overview of case studies performed under the BIGCCS framework and brings together the results of three latest studies. Two of these studies focus on comparison of technologies for CO_2 capture from a) an Integrated Gasification Combined Cycle, and b) a coal fired power plant and a cement plant. The third case study looks at valuation of CO_2 for Enhanced Oil Recovery.

The first study shows that CO_2 liquefaction capture from an IGCC is 23% cheaper in average than when using Selexol capture, and offer interesting synergies with CO_2 shipping. The second study presents a graphical methodology for systematic and consistent design of membrane processes for post-combustion capture and illustrates how the resulting designs lead to lower costs than those in literature and competitive compared to the "standard" Monethanolamine process. The third case study evaluates the economic value of CO_2 for EOR applications and demonstrated that a CCS chain including CO_2 EOR would overestimate its benefits if it does not considered other EOR techniques as an alternative to CO_2 EOR for Oil & Gas companies.

The presented case studies illustrate how the methodology and tool could be used to provide support for technology selection. Additionally, the tool allows smart design and operation of CCS chains and thereby enables selection of most suitable CCS chain configurations for specific cases with respect to techno-economic and environmental impacts.

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