Profiting from CCS innovations:
A study to measure potential value creation from CCS research and development

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Abstract

Globally, large private and public funds are invested into CO_2 capture and storage (CCS) research to provide the knowledge and technology required to mitigate CO_2 emissions below a sustainable level. A pertinent question to ask is whether this is the best way of spending limited resources. This paper presents a study aiming to quantify the potential economic gains from selected CCS innovations created in the international research centre BIGCCS and its successor NCCS. Development of CCS technology is currently driven by technology push and the lack of a market makes it hard to predict future potentials for increased revenue. Consequently, the study investigates potential cost reductions from implementing the innovations in full-scale industry projects based on qualified assumptions. The results show that even with limited deployment of CCS the potential cost savings from implementation of the innovations by far exceed the research investment. Additional value not considered is in this work is expected from commercialisation of the technologies for the technology providers, improved competitive edge for providers of CO_2 free products and enhanced safety for people, equipment and environment. By developing illustrative examples from technology innovations, the study aims to contribute to a broader public CCS debate addressing also potential gains and commercial opportunities in addition to the current focus on costs and safety.

Keywords: CCS; innovation; value creation; cost reduction; CO_2 capture; CO_2 transport; CO_2 storage; CO_2 value chain.

1 Introduction

The Paris Agreement represents a global action plan to avoid climate change by limiting global warming to well below 2^{o}C. CO_2 capture, transport and storage (CCS) is identified as one of the most promising measures for reducing the CO_2 emissions at a pace required for the world to meet the ambitions of the agreement and without CCS the task will be more demanding, if at all possible (IPCC, 2014). Future mitigation scenarios presented by the International Energy Agency (IEA) (IEA, 2017) confirm that CCS is needed and show that climate mitigation costs are expected to increase by 140 % if CCS is excluded.

However, the CO_2 abatement costs has been a major concern and with good reason. The development of new technologies along the CCS chain has been challenging and all industry experience shows that first-of-a-kind projects are subject to higher costs and more technical uncertainties than mature technologies. As a result, a large number of cost analyses have been presented over the two last decades (ZEP, 2015; Global CCS Institute, 2017). Some of them document that despite variations between projects, the costs are likely to drop as a result of anticipated cost reductions for CO_2 capture. Nevertheless, there seems to be a perception that CCS is very expensive and the fact that CCS may be the only measure to deeply reduce emissions from industry is often lost. In later years some published reports have addressed the value creation potential (CCSa, 2017; ETI, 2017; Bellona, 2015), but they are still few and far between.

As a consequence, six Norwegian industry confederations in 2018 asked SINTEF to carry out a study to investigate industrial opportunities and employment prospects in large-scale CO_2 management in Norway (Størset et al., 2018). The study placed emphasis on potential value creation and employment and was based on CCS scenarios in line with IEA and IPCC climate scenarios and assumptions regarding the evolvement of a CCS industry. The study showed a potential securing 80-90 000 jobs in process industry, natural gas and natural gas to hydrogen operation and shipping by 2050 and creating between 160 000 and 200 000 jobs in a Norwegian CCS industry and in businesses providing products and services to the industry. These numbers are highly relevant for Norway at a time where oil production has reached its peak. The report received wide-ranging attention and even though it is not a scientific study of value creation it demonstrated the value of bringing the potential upside of an industry related to CCS into the national debate.

For many business areas, effects of research can be documented based on assessment of actual commercial value and profits from implementation of technology. Furthermore, future potentials can be predicted based on known reference and business scenarios. The lack of a commercial market for CCS makes it more challenging to predict upcoming business opportunities and thus assess the value of scientific and technological progress. Nevertheless, to motivate continued investments in research critical for future sustainable energy solutions, it is essential to document the anticipated commercial value of future deployment of CCS technology.

Inspired by the value creation study on employment, it was therefore decided to conduct a similar investigation to evaluate the economic potential of selected innovations created in two international research centres on CCS; the Norwegian CCS Research Centre NCCS (Brunsvold et al., 2018) and its predecessor BIGCCS (Mølnvik et al., 2013). Based on a systematic assessment of the innovations, the potential cost savings from applying the technology were screened together with opportunities for commercialisation of products and services. To show the order of magnitude of the economic potential some simple illustrative examples were established.

The reported work is not an exhaustive cost study, but an assessment of economic potentials if more than a few CCS industry projects become a reality. In that case there will be a market for CCS technology. The study aimed to clarify to what extent the cost saved from using the innovations created in NCCS and BIGCCS in full-scale industry projects would match 16 years of investments in CCS research and give a qualitative assessment of opportunities for commercialisation of the technologies. The results can serve as basis for a simplified evaluation of the profitability of CCS research.

2 Background – CCS research in Norway and potentials of innovation

Since the introduction of the CO_2 tax in 1991, Norway has been a pioneer in the field of CCS:

- More than 20 years of experience on commercial CO_2 storage in the industry projects Sleipner and Snøhvit (Furre et al., 2017),
- Built Test Centre Mongstad (TCM) - the world's largest test centre for developing and validating new CO_2 capture technologies (TCMDA, 2018)
- Established the extensive public funding program CLIMIT managed by the Research Council of Norway (research and development) and Gassnova (demonstration and pilots) (CLIMIT, 2018; Gassnova, 2018a)
- Actively participating in EU research programs (FP6, FP7 and H2020, in the field of CCS)
- The Norwegian government plans to realise a full-scale demonstration of CCS with CO_2 from two industry sources by 2022.

In collaboration with industry and the authorities, the Norwegian research institutes and universities have played a leading role in building CCS research infrastructure and the competence imperative for developing knowledge, methodologies and technologies required to make CCS a viable measure to cut the CO_2 emissions. Over the last 15 years a large portfolio of research projects has boosted national and international research and development, addressing challenges along the whole CO_2 chain.

In 2009, the **BIGCCS International CCS Research Centre** (Mølnvik et al., 2013) was established as the first CCS research centre in Norway. The primary goal of this 8-year research programme was to enable sustainable power generation from fossil fuels based on cost-effective CO_2 capture, safe transport, and permanent underground storage of CO_2. BIGCCS was mainly funded by the Research Council of Norway and participating industry partners. It was led by the research institute SINTEF and involved several leading international research institutions. A comprehensive educational program resulted in 26 PhDs, 8 post docs and 52 master theses. BIGCCS's cumulated budget was 36 million € and about 50 million € when including the spin-off projects. Moreover, during the centre lifetime 46 new innovations emerged (Mølnvik et al, 2016.). Several of the innovations are further developed in the research centre succeeding BIGCCS; **the Norwegian CCS Research Centre (NCCS)** (Brunsvold et al., 2018). NCCS has an even stronger industry focus. It aims to enable fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects. Based on financial support from the Research Council and a strong industry consortium, NCCS has an estimated budget of 48 million € over the centre period (2016-2024). NCCS will actively work to create additional spin-off projects, in particular innovation projects closer to commercialisation (higher technology readiness levels, TRL) than the more fundamental research activities planned in the centre. Combined, the budgets of BIGCCS and NCCS with spin-off portfolios will exceed 100 million €.

Over time, it has been shown that companies collaborating with academic institutions have a superior output of new innovations, compared to those operating only within their own organisation (Nieto and Santamaria, 2007; Fabrizio, 2009). However, to release the full potential of university-industry cooperation it is important to identify how the scope of research is adapted to meet the industries' future needs, how the research is kept relevant despite changing and uncertain conditions, and how the research results can be transferred to the industries for them to utilize the takeaways (Adler et al., 2009). These aspects are highly relevant for research within CCS technologies, as much of the research efforts currently are performed under collaborative schemes such as EU's framework programme for research and innovation, Horizon2020, and national funding schemes for research centres and projects. Consequently, programmes for innovation and innovation transfer were established both in BIGCCS and NCCS.

What has not been addressed so far in in the BIGCCS and NCCS research is the future economic potential of the new innovations. If large scale deployment of CCS becomes a reality the innovations from CCS research are anticipated to represent a significant value creation potential for the centre's industry partners, as well as other commercial CCS actors. Therefore, the presented work has been conducted to quantify economic gains from application of new technology and thereby give a contribution to the quantitative valuation of the impact of CCS research.

3 Measuring value creation for CCS

As of 2018, there are 17 operating CO_2 capture plants worldwide, while five are being built. The total capacity of these plants are 38 million tonnes of CO_2 captured annually (Global CCS Institute, 2018). In addition, there are 15 CO_2 capture plants being planned worldwide, with a total CO_2 capture capacity of 27 million tonnes of CO_2 annually. Hence, the current and planned CO_2 capture plants will have a total combined capacity of 65 million tonnes of CO_2 captured annually.

IEA's 2 degrees scenario implies that by 2050, CCS has to account for approximately 12% of all green-house gas abatement, representing more than 6 billion tonnes of CO_2 captured and stored annually (IEA, 2016). This represents an average growth of more than 15% per year, from now and until 2050, a very significant annual market growth for CCS technologies over a period of more than 30 years. However, the roll-out of CCS is taking place in a pace much slower than this. New technological developments and innovations are created not because of a strong market pull, but rather almost entirely through technology push, in the absence of a well-functioning market.

The lack of economic drivers imposes a challenge when aiming to measure value creation from research on CCS technologies. The market is still immature and only a few technologies or new innovations are demonstrated in industry projects. One example is amine-based post combustion capture technology, commercialised e.g. by Flour (Flour, 2008) and Mitsubishi Heavy Industries (MHI, 2015) Consequently, to assess the potential of technologies, the current study had to assume that a *future market for CCS will develop*, and that innovations from research and development will be employed in this future market. The anticipated size of the market and the market share for each technology must be subject to discussion, but this basic assumption sets the frames for a quantitative assessment of potential future value creation.

For a power producer or energy intensive industry actor, CCS is first and foremost an enabler of more sustainable products (i.e. with a lower carbon footprint), and CCS comes with a certain investment and operational cost. However, these investments are expected to be necessary for maintaining a competitive industry, based on the assumption that in a carbon constrained world, there will be no room for industry emitting large amounts of greenhouse gases. Following this rationale, one might argue that CCS technologies is prerequisite for maintaining business in several industrial sectors, and that those who do not adapt will run out of business. Consequently, CCS technologies might form the foundation for very significant value creation in the future.

This rationale, however, is based both on the assumption on large scale roll-out of CCS, *and* on the assumption that there will be no room for emitters what so ever. Even though the ambitions of the Paris agreement and future climate scenarios, as the IEA scenario, establish that this must happen, it is hard actually measure or calculate the potential value creation from CCS innovations under these circumstances, because of the uncertainties and many assumptions.

Consequently, when estimating the potential value creation for innovations within CCS technologies, it is more accurate and thus relevant to consider reduced investment or operational expenses compared to business as usual or conventional technology, rather than potential increased revenues – even though the latter may prove to be even more important in the long run. With this approach the current study investigated whether the potential cost reductions from a few selected CCS innovations, exceed the investments in the research over the course of the lifetimes of the BIGCCS and NCCS research centres.

4 Method

In the BIGCCS research centre, 46 new innovations where reported and documented. These served as the starting point for this study. Several of the innovations are also being further pursued in the NCCS centre. The motivation was to investigate innovations which would have a high commercial potential in a future market for CCS, which covered the whole value chain for CCS, and which could be communicated clearly to a general audience, i.e. non-CCS-experts.

After screening the 46 BIGCCS innovations, six were selected to be included in the study. A seventh innovation on solvent technology with high TRL was also included. Research in the forerunner project BIGCO2 was important to the innovation and the results served as starting points for further research in BIGCCS and NCCS. The selected innovations cover the whole CCS value chain and comprise new technologies, new methods, and new simulation tools. The aim was to establish the value creation potential from each of these innovations, and as argued in the previous section, it would be more relevant to consider reduced investment or operational expenses, rather than increased revenues. Consequently, for the seven innovations, the value creation potential using one or several of the following principles was investigated:

- Lower investment costs or operational costs compared to reference because of new or improved technology or method.
- New technologies or methods making investment obsolete (i.e. enabling reuse of existing investments)
- Lower heat or electricity consumption compared to reference because of new or improved technology or method.
- New technologies or methods drastically reducing other operational costs compared to reference.

Each of the seven cases were approached first by conducting in-depth interviews of the key researcher responsible for the innovation. A main purpose of the interviews was to understand the details of the innovation, and how its application in a future CCS market could contribute positively to value creation, following one or several of the principles listed above. For each of the cases two to three interviews were carried out.

Based on the understanding gained in the interviews and review of relevant literature, case examples showing the application of the different innovations were established in close collaboration with the key researchers involved in each case. These seven examples illustrate how implementation of the new technology/method/tool in a single project can create value or reduce costs, both *qualitatively* (through description), and *quantitively* (measured in actual Euros). Thus, examples can be application of a new or improved capture technology applied for *one* industrial plant; a new design tool used for designing *one* CO_2 pipeline; or a new method for monitoring applied for *one* CO_2 storage reservoir.

For developing these examples, available quantitative data had to be combined with qualitative assumptions regarding each case. The results are therefore to a large extent based on expert assessment and intended as illustration of potentials and feasibility, more than exact science or economic calculation. For separating clearly between data and assumptions based on best available information, it was essential that all reasoning was transparent, and that all assumptions were made explicit.

One could argue that it would be relevant to extrapolate the results from each case covering a single investment (i.e. one capture plant), to the entire future market for CCS, or a sub-market, in line with CO_2 capture, transport and storage scenarios for Europe in 2050. This exercise would, however, require not only assumptions regarding the future deployment of CCS, but further assumptions of applicability of the technology, relevance, market share etc. The current study concluded that the level of uncertainty entailed in such an approach would significantly limit the value of the results. Nevertheless, to highlight the overall potential for value creation the innovations could have in a future full-blown roll-out of CCS, the topic is elaborated on in *Section 6 Discussion.*

5 Results

In this section, the seven innovation cases under investigation are presented. For each case, a general description of the innovations is given followed by example(s) of the potential value creation from each case, when applied once in a CCS project. Finally, additional effects from realising the innovation are described. The overall value creation potential for realising the innovations as part of a large-scale CCS deployment scenario is discussed in *Section 6 Discussion.* The maturity of the technologies varies from Technology Readiness Level (TRL, as defined by the European Commission) 4 to TRL 8, and the evaluation presupposes that the innovations are matured and further developed to commercial state and subsequently, industrially deployed.

5.1 Case 1: Energy- and cost-efficient CO_2 capture – the SOLVit project

Full-scale CO_2 capture requires large amounts of energy and the capture costs represent the main budget element of the CCS chain. About 40 % of the global CO_2 emissions stems from 4 000 point sources, many of them are found in low cost countries like India, China and Russia. To achieve global deployment of CCS it is imperative to significantly drive down the capture costs.

The SOLVit project (2008-2015) was initiated by Aker Clean Carbon, SINTEF and NTNU. The goal was to develop improved and more cost-efficient CO_2 capture methods and to enable Aker to become a leading vendor of CO_2 technology in the international market.

Building on extensive research fuelled by the introduction of the CO_2 tax at the Norwegian continental shelf in 1991 and later the Kyoto agreement, and supported by public funding from Gassnova established in 2005, SOLVit soon became a national and international flagship on development of CO_2 capture technology.

The SOLVit technology is based on advanced solvents binding the CO_2 in the flue gas from industry sources. It reduces the energy need for solvent-based CO_2 capture by 35 % and allows compact capture plants (Graff, 2016). Knowledge and infrastructure built in the project is a key for implementation of commercial full-scale CO_2 capture in Norway and globally.

At present Aker Solutions offers commercial CO_2 capture solutions based on the technology developed in SOLVit. The technology is installed and tested at test centre Mongstad (TCM). Furthermore, the technology is planned installed at Norcem-Heidelberg cement plant in Brevik in 2022, and is thus part of the Norwegian full scale project (Gassnova, 2018b).

Economic potential of the SOLVit technology's reduced energy need – example:

- Reduced energy need resulting from the SOLVit technology represents about 0,8 kg steam per kg CO_2.
- If one assumes a steam cost of 10 €/ton the cost saving is about 8 €/ton CO_2
- For a plant capturing 100 000 tons CO_2 per year will total cost saving be 800 000 €/year
- In addition, there will be significant reduced loss of solvents
- **Total cost reduction is 1 million €/year for a plant capturing 100 000 tons CO_2**

The technology is applicable to industry sources such as cement, steel, and waste incineration, as well as power production from natural gas and coal. These sources represent 40 – 50 % of the global CO_2 emissions.

Additional effects of the SOLVit project:

- **Costs avoided /revenue:** In addition to lower cost due to reduced energy use, the robust and compact technology allows reduced use of materials for manufacturing and the stable solvents limits the need for adding more solvent during operation.
- **Environmental benefits**: The technology captures 85-95 % of the CO_2 from various flue gases, and the use of environmentally friendly solvents allows emission of cleaned waste gas.
- **Benefits for society**: The competence building in SOLVit is based on a close collaboration between research and industry. SINTEF and NTNU has become world leading within the area, several PhDs are educated, and Aker has taken a leading position among international industry actors within CCS.
- **Industrialisation:** Aker Solutions has become a competitive vendor of capture plants in a global market – and has conducted tests globally. In addition, Aker has developed a modular capture plant, Just Catch (Knudsen, 2017), suited for installation at smaller point sources which currently is sold in the international market.

5.2 *Case 2: CO_2 capture and liquefaction for ship transport*

If the CO_2 is to be transported by ship in a given CCS chain, the CO_2 must be liquified prior to transportation. This is the case e.g. in the Norwegian Full-Scale project (Gassnova, 2018b). In most concepts for CCS chains, the CO_2 is liquified *after* it is captured, as a separate process step. The current innovation represents a novel concept where the CO_2 liquefaction process is an integrated part of the capture process. By combining the liquefaction process with an upstream capture technology into a hybrid CO_2 capture concept, significantly more efficient CO_2 capture can be achieved, while simultaneously producing liquid CO_2 at ship transport specifications (Berstad et al., 2013). Membranes or absorption technologies are good candidates for hybrid concepts.

The CO_2 capture through liquefaction concept can be used for post combustion capture, or more promising for CO_2 separation from syngas, producing hydrogen and CO_2. In the latter case, the hybrid technology will be capable of producing very pure hydrogen, and at the same time maintaining the purity of the CO_2 product, i.e. liquid CO_2 at a purity of >99% - a result which a single stand-alone CO_2 capture process will not be able to. For separating CO_2 from syngas, cost reductions between 30-40% have been showed to be achievable, compared to standard solvent technologies (selexol) (Jordal et al., 2013)

<u>Economic potential of liquefaction as cost-efficient CO_2 capture technology – example</u>

By capturing CO_2 from a cement plant, based on a power price of 0,03 €/kWh and a Norwegian power mix (majority of hydropower), techno-economic studies show a significant potential for reducing CO_2 capture costs by using the hybrid capture and liquefaction technology, compared to standard solvent technology (MEA). The cement plant emits **1 million tonnes of CO_2 per year,** which is captured using a hybrid membrane-liquefaction technology (Voldsund et al., 2019; Gardarsdottir et al., 2019):

	Standard technology (MEA)	CO_2 capture by membrane-liquefaction hybrid	Cost reduction	Relative improvement
Cost of CO_2 avoidance [€/tonne CO_2]	73	65	8	11 %
Annualised capture cost [million €]	73	65	8	11 %

The CO_2 is delivered at liquid state at specifications required for transportation by ship. The potential for reducing costs is shown to be even larger when separating CO_2 from syngas, for producing hydrogen.

Additional effects of the new liquefaction technology:

- **Reduced energy need:** The innovation has an overall lower need for energy because of the integrated CO_2 capture and liquefaction process. Further, the technology is truly end of pipe, and requires no integration with the existing industrial plant, only electricity is needed. Thus, potential for retrofitability is high.
- **Environmental benefits**: A hybrid concept of membranes and liquefaction requires no solvents or other materials consumed in the process. The technology is therefore environmentally benign. Also, in the case of syngas separation, the technology enables production of both high purity CO_2 and H_2, while maintaining a capture rate >90 %.
- **Industrialisation:** It is a potential for establishing new vendor industry based on the innovation, especially in the expanding market for producing hydrogen from syngas.

5.3 *Case 3: Chemical looping combustion for cost efficient CO_2 capture*

Chemical looping combustion (CLC) is a CO_2 capture technology by oxy-fuel combustion. In CLC, the oxygen is produced as an integrated part of the capture process. Hence, no air separation unit (ASU) is needed, and significant cost and energy savings can be achieved. CLC is based on that small metal oxide particles circulate between two reactors which operate at a temperature between 900 and 1000 °C. In the first reactor, the metal oxide will take up oxygen from the air, whereas it is released in the second reactor where the oxygen is used to combust a fuel.

The CLC research in FME BIGCCS and related projects has focused on advancing and validating chemical looping combustion for CO_2 capture at industrial scale. A reactor concept has been developed, which is based on coupling two circulating fluidised bed (CFB) reactors together resulting in a full CLC process. The CFB technology is commercially available and using it to realise CLC is considered as an attractive alternative for establishing a full-scale plant. The concept is tested in a pilot scale unit (150 kW_{th}), where also new metal oxides are validated (Langørgen and Saanum, 2018; Langørgen et al., 2017).

The overall purpose of the research is to bring down capture costs, which represent a major cost component of the CCS chain. CLC also represents a readily alternative for capturing CO_2 from industrial plants which already have CFB reactors, e.g. biomass-fired combined heat and power (CHP) plants. Used in such applications, CLC can also enable negative emissions, i.e. net reduction of CO_2 in the carbon budget, which will be key for reaching climate targets globally.

Economic potential of CLC as a cost effective CO_2 capture technology – example

Several studies have showed the potential for CLC technology. Lyngfelt et al. (2015) show in their study that CLC has the potential of becoming a cost-effective CO_2 capture technology. The study evaluates the technical, operational and cost differences between a conventional "circulating fluidised bed" (CFB) plant with a 1000 MW_{th} boiler using solid fuel, producing approximately 400 MW of electricity, and a corresponding CLC plant (so called CLC-CFB). Using CLC as capture technology, CO_2 avoided costs can be reduced by 30%, compared to conventional technology:

- *CO_2 capture cost:* *26 €/tonne CO_2*
- *Reduction in electric plant efficiency:* *4 %-points*

A thought example with 150 MW_{th} plant (relevant size for the Nordic region) will emit approximately 440 000 tonnes of CO_2 per year. Based on the numbers above, this results in:

- *Annual CO_2 capture cost, conventional technology:* *16,3 mill. €/year*
- *Annual CO_2 capture cost, CLC:* *11,4 mill. €/year*
- *Annual difference (reduced costs):* *4,9 mill. €/year*

Additional effects of the CLC capture technology:

- **Environmental benefits**: CLC has a great potential for integration with combustion when biomass is used as fuel. CO_2 capture from such process gives so called "negative emissions", effectively removing carbon from the natural carbon cycle in the atmosphere.
- **Industrialisation:** There is a large potential for use of the CLC technology, where a prime application is medium scale co-generation plants (both heat and electricity) where biomass, other biofuels or recovered waste is used as fuel.

5.4 *Case 4: Preventing running ductile fractures in CO_2 pipelines*

Transportation of large volumes of CO_2 in pipelines to a reservoir requires high pressure compression (approximately 100 atm) and a possible problem is *running ductile fractures*. A small crack or damage on the pipeline can expand and run along the pipeline in both directions (thus running fracture). In a worst-case scenario, the pipeline can fracture for several hundred meters, which can cause large damages, as well as dangerous leakages of CO_2. The risk of running ductile fracture can be reduced by increasing the wall thickness of the pipe or by using steel of higher quality. Both options are costly.

For evaluating whether a crack can develop into a running ductile fracture today, semi-empirical methods based on full-scale experiments on natural gas pipelines are being used. When translating this into design specifications for CO_2 pipelines, safety margins in the form of thicker steel pipelines are added.

The innovation in case 4 addresses this challenge. It is an advanced simulation model/tool, which can predict whether a crack or damage on a CO_2 transport pipeline will develop into a running ductile fracture (Nordhagen et al., 2017; Aursand et al., 2016). The model can be used to determine whether existing pipelines for natural gas can be reused for transporting CO_2 as well as assessing situations with varying or changed operating conditions. The model can also be used for designing new CO_2 pipelines and establishing reliable safety factors for the semi-empirical methods.

Economic potential of reducing safety margins for CO_2 pipelines – example

When the running ductile model can be used for reducing safety margins for CO_2 pipelines, the wall thickness of the pipelines can be reduced, and hence the overall need for steel. If the wall thickness of a 36" pipeline can be reduced by 10-15%, the reduced need for steel amounts to ca 68kg of steel per meter of pipeline (see table below). This corresponds to about 50 €/meter in steel savings.

For a CO_2 pipeline of 500km, the total savings will constitute about 25 million €. Less steel (appr. 34 000 tonnes) will as well reduce CO_2 emissions by about 60 000 tonnes. The example is theoretical, but illustrates the magnitude of potential savings from profiting from this innovation.

Example: reduced costs for steel for a 500km CO_2 pipeline		
Pipeline diameter 36"	914	mm
Typical wall thickness for 36" pipelines	20-30	mm
Reduced wall thickness (example, 10-15%)	3	mm
Price steel[1]	0,75	€/kg
Weight steel	7 850	kg/m^3
Reduced steel pr. meter pipeline	68	kg/m
Reduced cost of steel pr. meter pipeline	50,8	€/m
Reduced cost of steel for 500 km pipeline	**25,4**	**mill. €**
Reduced emissions[2] (500 km * 68 kg/m * 1,87 kg CO_2/kg pipeline)	63 600	tonne CO_2

[1] MetalMiner, 2018. Sourcing & Trading Intelligence for Global Metals Markets. https://agmetalminer.com/metal-prices/carbon-steel/ (accesses 14 July 2018).
[2] NACAP, 2018. Carbon Footprint of Pipeline Projects. http://www.iploca.com/platform/content/element/7551/NacapPresentationCarbon-FootprintofPipelineProjects.pdf (accessed 26 September 2018).

Additional effects of the running ductile fracture-tool:

- **Reduced uncertainties:** The new tool will reduce the uncertainty when designing new pipelines and when requalifying existing pipelines for new applications:
  - Re-qualification of existing natural gas pipelines for CO_2 transport saves investments.
  - Documentation of safe design increases chances for implementing CCS projects.
- **Reduced costs:** Reliable simulations of CO_2 pipelines enables better optimisation of material quality and material costs in addition to wall thickness. High quality simulation models will also reduce the need for full-scale pipeline experiments, which are very expensive.
- **Industrialisation:** The simulation tool has a commercial potential, and can form the basis for a start-up company, or new business in existing industry. However, the model is still under development.

5.5 Case 5: Cost-efficient methods for geophysical monitoring:

CO_2 capture from European industry will require storage of several millions tons CO_2 each year. It is documented that the Norwegian and UK continental shelf can store European emissions (Norwegian Petroleum Directorate, 2011; Senior, 2010), but this makes demands on the documentation of operational safety and permanent storage of CO_2. Continuous monitoring of CO_2 in the reservoir and identification of possible migration paths is therefore needed. Geophysical methods, mainly seismic methods, are currently used for mapping and monitoring the subsurface (Furre et al., 2017), but the methods are expensive. Extensive research is ongoing to develop cost-efficient methods with accuracy needed to underpin operational decisions and ensure safe and successful injections.

Economic potential of cost-efficient monitoring methods – example

A main contribution to profitability is related to **reduced costs for monitoring surveys** because of more targeted measurements, better use of data and continuous validation of CO_2 behaviour. If the innovation enables that:

- The time between surveys is 50 % longer than current standards
- Every second survey is targeted and thus 50 % cheaper

a storage project with 20 surveys á 10 million € has a potential for 50 % cost reductions – amounting to 100 million € for one project. Cost per survey is indicative and will depend on type and size of field.

Additional effects of new monitoring methods:

- **Costs avoided** because more accurate information reduces risk of unforeseen events e.g. temporary halt in operation, extra survey, unplanned well intervention, extra injection well, early termination of project before 20 years.
- **Environmental benefits** in addition to avoided CO_2 emissions from CCS are achieved as the risk of CO_2 leakage is reduced, emissions from maritime activity are reduced and overall use of material is reduced.
- **Benefits for society** due to improved ability to fulfil regulations, enabling safe CO_2 storage and public acceptance for CCS as a measure for curbing CO_2 emissions
- **Industrialisation:** Technologies for monitoring of reservoir and wells are suited for commercialisation and have great potential for transfer to traditional oil and gas industry.

The innovation of Case 5 comprises results from longstanding research in NCCS and BIGCCS on integrated methods for accurate monitoring at lowest possible cost aiming at reducing the need for geophysical data by more optimal utilisation of available information. Novel methods based on new geophysical algorithms, integration of several types of data e.g. active/passive seismic, gravitation and electromagnetic data and new technology for collecting data give the operators more quantitative and detailed information about the CO_2 in the storage site and knowledge on the uncertainty of the available data (Dupuy et al., 2018; Dupuy et al., 2017; Romdhane et al., 2018).

5.6 Case 6: Improved integrity over the lifetime for CO_2 wells

Wells drilled into a CO_2 storage reservoir represent a potential risk for leakage in the CCS chain. This goes for active wells in operation, as well as plugged and abandoned wells. Cement is the prime material used for mechanically stabilizing the wells and preventing leakage through them. After a section of the subsurface has been drilled, a steel casing pipe is placed in the hole and stabilized by pumping cement into the annulus between the pipe and the drilled rock. This procedure is called *primary cementing*, and it forms a mechanical and hydraulic barrier in the underground. Also, for permanently sealing (plugging) a well, after its operational life, it is common to fill discrete sections of it with cement or cement-based material. Therefore, high quality cement barriers are imperative for the integrity of wells. This is especially important in a CCS context, since CO_2 is a reactive and buoyant fluid with high leakage potential. Over time, it can degrade the cement, and the thermal stresses arising during intermittent CO_2 injection are also higher than in normal oil and gas wells – and can jeopardize well cement integrity. In a CCS project, wells are also plugged at maximum pressure (instead of after depletion, as in oil and gas wells) – which poses an additional threat towards well integrity. It is possible, but expensive, to repair a poor primary cementing job, but there are at present no solutions for repairing a leaking plugged and abandoned well.

A portfolio of research activities has resulted in knowledge and methods to better ensure well integrity, making it possible to avoid a significant share of maintenance costs, to reduce investments and thus, enable more safe and cost-efficient CCS. The innovation of Case 6 includes:

- A new method for improved bonding between cement and steel, by using electric voltage (Lavrov et. al, 2016).
- A new tool for simulating pumping and placement of cement in the well, providing new understanding about what affects the cementing process. Near-wall particle dynamics, well hole geometry and centralisation of the casing are identified as important parameters (Lavrov and Torsæter, 2016; Torsæter et al., 2015).
- New understanding of how operational parameters affect the sealing capabilities of the CO_2 well, for instance hole cleaning before cementing and temperature variations during injection (Opedal et al., 2015; Lavrov et al., 2017; Torsæter et al., 2017).
- Improved understanding of how defects in cement can close up by precipitates forming during CO_2 leakage and how cements can be tailored for CO_2 wells (Kjøller et al., 2016; Panduro et al., 2017)

The work focuses on wells intended for CO_2 storage purposes, but the results are relevant also for oil and gas wells, wells for geothermal energy and scientific wells for improved understanding of the subsurface.

<u>Economic potential of improved cementing of CO_2 wells – examples</u>

Reuse of wells represent a significant cost-saving potential because it reduces the need for drilling new wells. If wells are constructed in a robust way, with tight primary cement, their operating time will be longer and the possibility for reuse higher. Drilling a new offshore well is associated with costs in the range of 50 mill € (Ruså, 2014).

Reduced plugging costs. After their operational life, all wells need to be permanently plugged. In a CCS context the goal is to ensure that no CO_2 migrates along the well. For difficult wells, the plugging operation can take up to 60 days, while easier wells can be plugged in as little as 20 days (Straume, 2014). The difference between easy and difficult is often the quality of the primary cement job. Offshore plugging operations require the use of large drilling rigs with high daily rates in the range of 0,5 million € (Oljedirektoratet, 2014). A simplified cost-saving example can thus be set up:

- Plugging of well with poor primary cement job: 0,5 million €/day*60 days = 30 million €
- Plugging of well with good primary cement job: 0,5 million €/day*20 days = 10 million €
- Saved costs of robust primary cementing of one well can be around 20 million €.

Additional effects of improved cementing of CO_2 wells:

- **Saved costs** is significant due to reduced risk of leakage, increased operational lifetime of wells, and reduced maintenance costs.
- **Environmental benefits** (in addition to avoided CO_2 emissions from CCS) are achieved as the reduced risk of methane leakage from older wells. Consequently, old wells can be reused which saves costs and it enables utilisation of CO_2 storage capacity. For onshore CCS scenarios, good well integrity also reduces the risk of groundwater contamination. In addition, there is a reduced need for rigs that would cause significant emissions of CO_2.
- **Benefits for society**: Acceptance among the public is more likely when it can be shown that CO_2 storage is permanent and therefore a long-term measure for reducing CO_2 emissions.
- **Industrialisation:** Optimal methods and products for cementing are relevant for commercial companies providing service to the actors of the CCS industry, with great potential for transfer to traditional oil and gas industry.

5.7 *Case 7: Smart design of CCS chains*

A CCS chain involves the whole value chain from CO_2 capture and until final, permanent storage. As no CCS chains are identical, in addition to often being scenario and case sensitive, each chain must be design individually for arriving on an optimal solution. Optimisation of each element in the CCS chain individually results in risk of sub-optimisation. One of the research challenges is therefore to develop consistent and transparent methods which takes technology, environment and economy into account when evaluating CCS chains. Increased knowledge and better tools for decision support will contribute to reduced uncertainty and risk when designing and evaluating full CCS chains.

The innovation in Case 7, consists in a new software tool, iCCS, for holistic system optimisation of CCS chains (Jakobsen et al., 2017). iCCS enables the user to compare CCS chains with different configurations, simulate different scenarios and find an optimal solution for choice of technology, environmental assessment, and costs. The potential for cost reduction is linked to integration and optimisation of the interfaces between the different elements of the CCS chain.

A new tool is developed for transparent, consistent and holistic optimisation of CCS chain design, taking technology, economy and environment into account. Initial analysis conducted by the research team indicates that optimal design may reduce overall costs of a CCS chain by 10 % or more (Jakobsen et al., 2017).

<u>Economic potential of optimised CCS chains – example</u>

Using the iCCS tool, the optimal storage option can be selected for CCS from a given cement plant. The tool can be used to evaluate the cost of transport to the storage site and the cost associated with CO_2 storage depending on the storage type and characteristics of the reservoir.

Evaluation of two storage options:

- Option A: Nearby offshore Saline Aquifer (SA) (300km from plant, pipeline transport)
- Option B: CO_2-Enhanced Oil Recovery (EOR) storage located "far" from the plant (700 km, ship transport)

Although option B is further away, it can significantly reduce operating costs (-10 M€/year) and CCS cost (-16 /tonne CO_2) as CO_2-EOR generate revenues.

Example: reduced costs for steel for a 500km CO2 pipeline

	Option A	**Option B**	**Reduction with option B**
Storage distance from plant [km]	300	750	-
Type of storage	SA	EOR	-
CCS CAPEX [million €]	242	241	~0%
Average CCS OPEX [million €/year]	22	12	-45%
CCS cost [€/tonne CO_2]	95	79	-17%

Additional effects of optimised CCS chains:

- **Better decision making:** iCCS is a standardised tool for critical evaluation of CCS chains. The tool gives increased understanding of interdependencies and elements within the CCS chain related to the choice of technology, environmental impact and economics. Examples of different evaluations can be CO_2 transport solutions, i.e. pipeline or ship (Roussanaly et al., 2013; Roussanaly et al., 2014a), comparison of different CO_2 capture rates for different technology options (Roussanaly et al., 2018), CO_2 capacity for different capture plants (Roussanaly et al., 2013; Roussanaly et al., 2014a), or different CO_2 storage solutions (Roussanaly et al., 2014b).
- **Industrialisation:** The iCCS tool is under constant development, but has already been used actively for specific cases in cooperation with industrial end-users. In the future, there is a high potential for commercialisation of the tool.

6 Discussion

The results from investigating the value creation potential of the selected innovations indicate that potential cost savings from applying the new technology once in an industry scale CCS project are in the range of 5 million € to 50 million €. So, what does this imply with respect to saved costs in a scenario where CCS is deployed at large scale to manage several millions of tons CO_2 every year? A simple extrapolation can serve as an illustration:

The example on saving costs by reducing safety margins for CO_2 pipelines by using the new tool for simulating running ductile fractures showed that the reduced wall thickness of the pipeline lowered the steel costs by 25,4 million € for a 500 km 36" pipeline (Case 4). A report by the CO_2 Europipe Consortium (Neele et al., 2010) estimates that the trunk pipeline required for an offshore only storage scenario for Europe is 33 000 km by 2050. Of this about 18 000 km has dimension 36" or more. For the sake of simplicity and to assure a conservative estimate it is assumed that all pipelines >= 36" are built with 36" and that 50 % of these pipelines, i.e. 9 000 km, are built with reduced safety margins. The saved costs in this example amounts to **457 million €** when the saved costs for 500 km pipeline is 25,4 €. If larger pipeline dimensions are taken into account and potential savings for dimensions below 36" are included, the number will be considerable larger.

Another example that can be extrapolated is related to reduced costs by ensuring robust cementing of wells (Case 6). The IEA 2050 scenario estimates that 320 million tonnes of CO_2 must be stored each year in Europe by 2050 (IEA, 2016). Assuming that one well can accommodate annual injection of 1 million tonnes of CO_2, 320 injections wells are needed. Additional wells that may be required such as appraisal wells and wells for remediation in case of pressure build up are not included, nor are wells for other purposes such as petroleum production and geothermal energy. A conservative estimate is that if 50 % of the wells are robustly cemented using state-of-the-art knowledge from the presented innovation, the saved costs for safe plugging of these wells will be 320*20 million € = **6 400 million €** compared with plugging costs of traditional wells with poorer cementing. For comparison, the total investment cost of the Norwegian full-scale project being planned is estimated to 1 280 million €, maybe somewhat lower as the number of point sources is reduced from three to two (Oslo Economics and Atkins, 2016).

Finally, an extrapolation can be made based on the SOLVit technology (Case 1). In the presented example it is estimated that the annual cost reduction for capturing 100 000 tonnes of CO_2 is 1 million €. The fact that the technology is applicable to various industry sources the potential distribution of technology is vast. To match the research investments in BIGCCS and NCCS (100 million €), savings related to reduced energy use over **10 years for 10 capture plants** is enough. Given that the SOLVit technology is applicable to thousands of industry plants, implementation in 10 plants is marginal.

The examples clearly demonstrate that the order of magnitude of saved cost from implementation of innovations from NCCS and BIGCC by far exceeds the research investment of 100 million €. That said, the examples and extrapolation rests on a set of simplifying assumptions, such as:

- The amounts CO_2 captured and stored by 2050 is similar to what IEA and IPCC display in their climate mitigation scenarios.
- The innovations created in NCCS and BIGCCS are applied for a certain share of the commercial CCS projects in Europe and globally.
- The economic effect of putting the innovations into use is comparable with the expert opinions included in this study.

Usually, assessment of results and effects of research are based on historical data on value creation from application and revenues from commercialisation of the technology. In the absence of a well-functioning carbon market and no market for commercial CCS technology, it is only more general CCS scenarios that can support predictions of how results from research can improve profitability of individual CCS projects and even enable the deployment of CCS at large scale. This makes methods for assessment of value creation challenging and scientific accuracy is not achievable. Nevertheless, to stimulate a discussion that goes beyond the potential costs of CCS it is important to outline also the potential gains and opportunities for business development. When assumptions are explicit and transparent, they can also be questioned, so that based on the collective knowledge of the CCS community we can develop a more realistic foundation for the discussion. Thus, a broader discussion is initiated and that is the primary motivation for conducting the presented study.

7 Conclusions

This paper presents the main scientific contributions of selected BIGCCS and NCCS innovations and estimates the value creation potential based on the estimated earned or saved value. Underlying key assumptions for each innovation are explained. Also, the paper illustrates how successful deployment of three of the innovations within the frames of the 2050 scenario potentially can contribute to overall commercial value. Additional qualitative effects such as improved storage safety and spill-over effects to other business areas as well as competitive edge for CO_2 free products are not included. Nevertheless, the study shows that the estimated potential value creation by far exceeds the 100 million € investments in the research leading to the innovations. Therefore, a main conclusion from the study is that CCS research and development is a valuable investment that can enable sustainable power and energy intensive industry while securing the profitability of the businesses. Furthermore, despite challenges in predicting market value of new CCS technologies and the need to make qualified assessments, the paper argues that to demonstrate the business case of CCS in a carbon restricted future and maintain the momentum for CCS deployment it is important that the international community discusses potential gains of large-scale CCS in addition to costs and safety issues.

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