IMPACT OF INNOVATIONS FROM THE NORWEGIAN CCS RESEARCH CENTRE (NCCS)

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Abstract

We have evaluated the potential impact of the research and innovation performed in the Norwegian CCS Research Centre (NCCS). In this context, impact was evaluated along several axes. Examples include reduced emissions, economic impact (increased value creation, saved cost), improved decision making, saved energy, and industrial potential. The reference system is the envisaged CCS network in Europe by 2030. The study illustrates how the research and expected innovations can impact CCS chains and society when applied.

Keywords: *CCS, innovations, impact*

1. Introduction

NCCS' main goal is to fast-track CCS deployment by timely delivery of safe and cost-efficient CCS technologies. This is facilitated by promoting an innovative environment through concrete collaboration between scientists and industry partners. As an international CCS research hub, NCCS is built to stimulate open innovation processes where companies involved in the Centre will be able to commercialize ideas and emerging technologies from outside their company borders, building on others' ideas and even bringing ideas from NCCS into new and emerging markets. This model optimizes innovation and technology output across company boundaries and increases the potential gain for each company involved, as the pool of ideas and concepts emerging from NCCS will be larger than that of each company.

Research within CO_2 capture, transport and storage is multi-disciplinary and covers a wide range of topics. Consequently, the outcomes have different characteristics with respect to type of innovation, maturity, and applicability in the CCS chain.

Building on the methodology from the Research Council impact study [1]-[2], NCCS has assessed the potential impact of selected innovations from the 12 NCCS research tasks covering the whole CCS chain, including CO_2 capture, transport, storage, and value chain. The innovations in this study mainly fall under four categories: 1) new technology, 2) models and simulation tools, 3) new methods, and 4) new standards and guidelines. The NCCS deployment cases serve as basis for the quantitative illustration of impact made for each innovation to indicate the order of the potential gains.

1.1 NCCS Deployment Cases – directing research for maximum impact

NCCS originally defined two CCS deployment cases (DCs) to help structure and align the research, and support NCCS in fulfilling its ambition to overcome critical barriers and accelerate CCS deployment. **NCCS DC2025 - CCS for Norwegian Industry** is similar to the Norwegian full-scale project and includes CO_2 capture from industry sources and transport with ship to ensure a flexible solution for CO_2 storage on the Norwegian Continental Shelf (NCS). One storage site in offshore aquifers is anticipated, with a capacity of 1-1.5 Mt/year in 2025 (**Figure 1**).

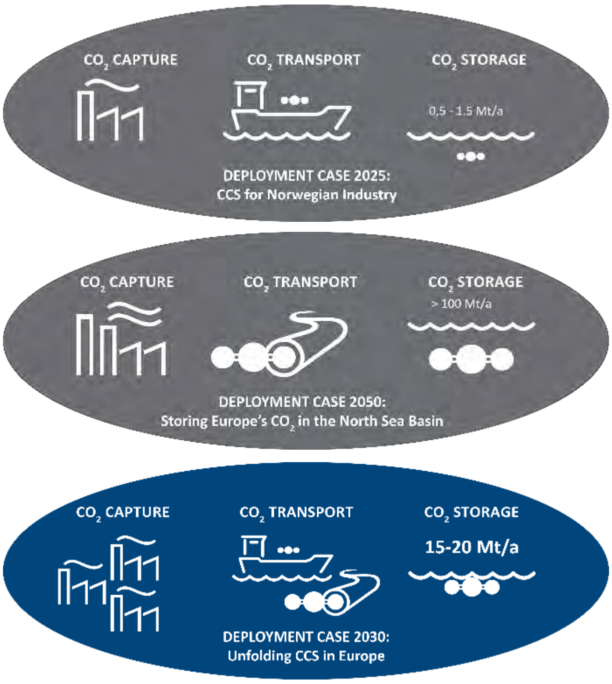

Figure 1. NCCS deployment cases: DC2025, DC2050, and DC2030

The second deployment case, **NCCS DC2050 – Storing Europe's CO_2**, comprises captured CO_2 from numerous sources in Europe and transport via a pipeline network to Norwegian storage sites in the North Sea. Several major storage sites are foreseen, some with an opportunity for EOR, with a storage capacity of ~100 Mt/year by 2050.

For this NCCS impact study a third deployment case is defined to serve as basis for analysis: **NCCS DC2030 - Unfolding CCS in Europe**. DC2030 incorporates all European CCS projects implemented, under construction and those planned to be in operation within 2030. It includes industry sources, power generation, natural gas processing and H_2 production. A combination of ship and pipeline transport of CO_2 to aquifers and depleted gas fields ensures flexibility. Capacity in 2030 is estimated to be 15-20 Mt/year, with the ambition to increase it to more than 40 Mt/year after 2030 (**Figure 2**).

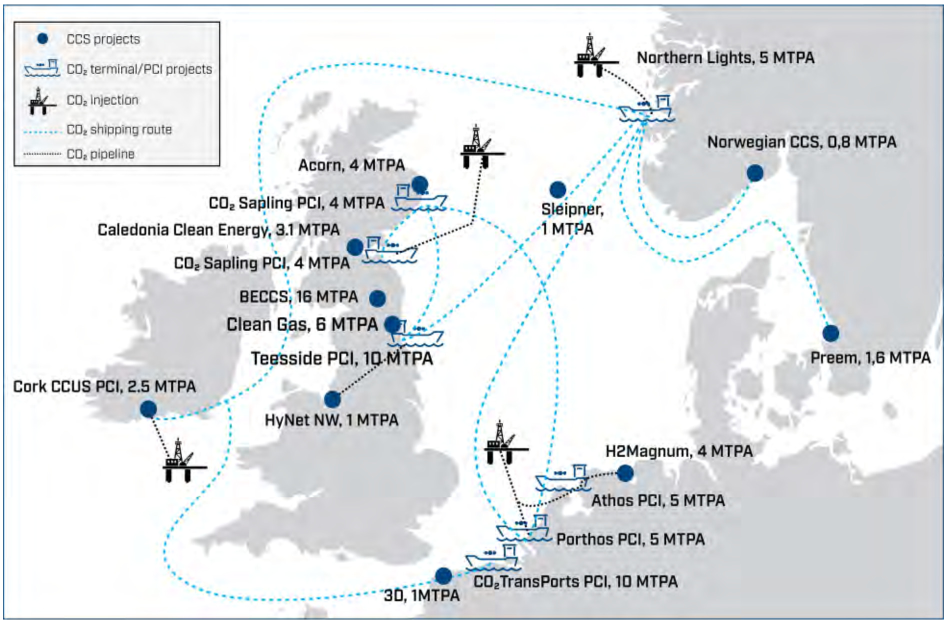

Figure 2. Projects included in NCCS DC2030 - Unfolding CCS in Europe (data source: [3], [4], project's webpages).

2. Expected impact from selected cases

2.1 Methodology

The case studies were conducted by the researchers within the 12 NCCS tasks in an iterative process, including dialogue with industry partners. For each case, the addressed challenge was documented before describing the innovation and its potential impacts if successfully implemented in a CCS project. To indicate the order of magnitude of potential economic impact, simplified illustrative examples were made for all cases. In the following, 6 of the case studies are summarized.

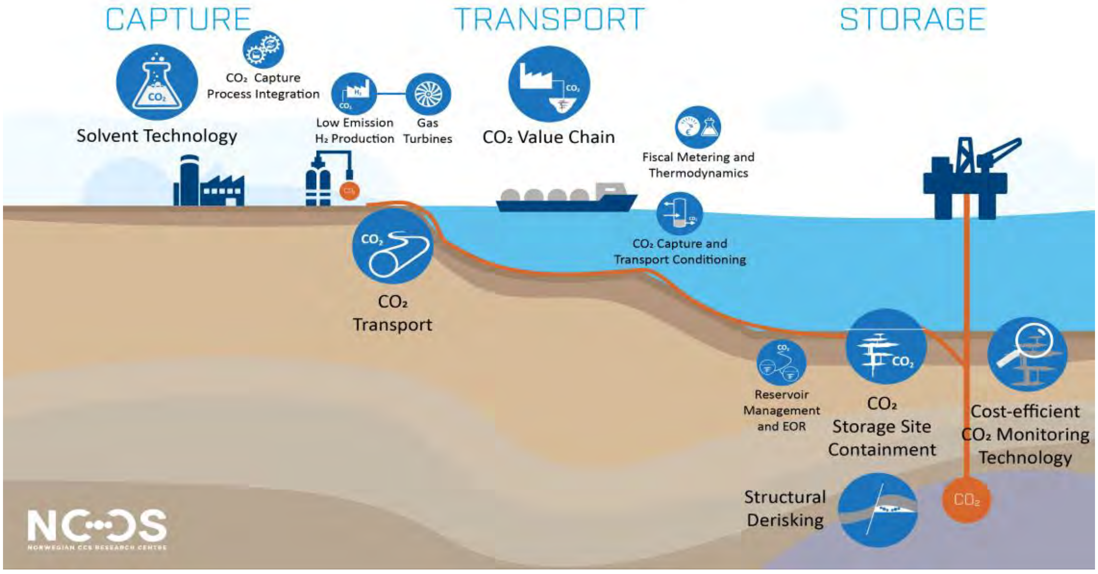

Figure 3: The 12 research tasks in NCCS cover the whole CCS value chain. 6 tasks (larger circles) contributed with the case studies presented in this paper.

2.2 Impact evaluation for selected case studies

***Case 1** – Solvent loss reduction in amine-based CO_2 capture*

Main impact:

Reduced OPEX and improved safety in operation and operational environment

The challenge:

During chemical absorption, CO_2 present in a flue gas is absorbed and chemically bound to a solvent. The reaction is reversed during solvent regeneration and the solvent is reused to absorb CO_2. A part of the solvent will react with other compounds in the flue gas forming compounds that cannot be regenerated. Formation of unwanted compounds depends on the composition of the flue gas, the solvent used and the operation of the pilot plant. Over time, these reactions lead to loss of capture efficiency, and could cause problems such as corrosion, fouling, foaming, and increased emissions.

The innovations:

- Technologies for removal of oxygen and iron from the solvent to reduce degradation.
- Methodology for identification of solvents with higher chemical stability

Potential impact:

Base case for illustration: 2 Mt/yr CO_2 captured from two power plants using 30% MEA-based solvent technology in DC2030. With MEA cost of 2 €/kg and solvent degradation rate of 2 kg MEA/ton CO_2, the cost of solvent loss is 8 M€/year.

Estimated effect from implementing NCCS innovations for oxygen and iron removal is up to 50% lower degradation of MEA based solvent. This would give potential savings up to 4 M€/year in replacement cost of the active solvent components.

Besides, the methodology for predicting chemical stability based on structure - degradation relationship for various amines would enable selecting a stable solvent at early stage of the solvent development.

***Case 2** – Increased storage capacity with improved geological fault models*

Main impact:

Reduced uncertainty resulting in improved safety for storage sites and increased storage capacity.

The challenge:

Implementation of large-scale CO_2 storage will require utilization of a wide range of storage reservoirs including faulted reservoirs with structural traps. The sealing properties of faults are challenging to predict, and conservative estimates and high uncertainty may limit the total injection volume or even disqualify a storage site. Existing industrial models have limitations when addressing fault risk related to CO_2 injection in faulted aquifers.

The innovations:

An improved fault de-risking framework that includes dynamic pressure changes related to CO_2 injection and addressing along-fault fluid migration. Such a framework would:

- Reduce uncertainty related to fault properties
- Increase confidence in site integrity and confinement
- Enable qualification of increased storage capacity

Potential impact:

The development of the Horda Platform area for CO_2 injection showed that high uncertainty in existing fault seal prediction models for shallow, fault-bound aquifers like Smeaheia (**Figure 4**), limits the capacity and provides major obstacle for site qualification. The Norwegian CO_2 storage atlas [5] indicates around 40 Gt storage capacity in Norwegian North Sea aquifers. The effective volumes found suitable for safe and long-term storage during technical maturation may be as low as 10% of the estimated capacity.

For the Norwegian North Sea this gives a suitable safe capacity around 4 Gt. Assuming this volume could be increased with roughly 10% if risk related to fault sealing is reduced, a total increase in storage capacity of 400 Mt can be estimated, enabling 20 years of storing 20 Mt CO_2/year (NCCS DC2030). Improved fault seal models and reduced uncertainty is a necessary, although not sufficient, step towards qualification of additional storage capacity.

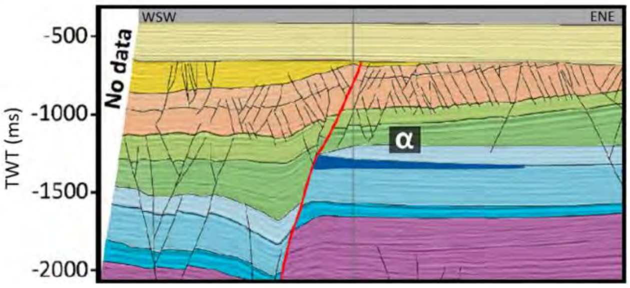

Figure 4. Seismic section with fault interpretation for Smeaheia [6], modified from M. Mulrooney.

***Case 3** – Models for identifying optimal conditions for transport of CO_2 via ship*

Main impact:

Showing potential reduction in CAPEX and OPEX in future projects with lower pressure-based CO_2 transport.

The challenge:

CO_2 shipping is expected to play an important role in early CCS development, for "small" capacities, and/ or "long" distance transport. Over the last few years, questions on optimal transport conditions (T and P) have been raised. Although the density of liquid CO_2 decreases, and the costs of storage tank and ship increase, with increasing pressure, the cost of liquefaction is higher for the lower transport pressure. 15 bar is currently considered the best option for the Norwegian full-scale project, based on maturity and safety. However, work in NCCS has shown that in the future, lower pressure-based transport could be a better solution due to its potentially lower cost.

The innovations:

A tool for identification of optimal conditions (pressure, temperature) for transport of CO_2 by ship that would lead to significant reduction in the costs of CO_2 liquefaction and transport. The transport conditions of interest are especially the low-pressure option (7 bar) and the medium-pressure option (15 bar).

Potential impact:

Base case for illustration: A possible case within DC2030 is transport of 5Mt/yr CO_2 from Netherlands to Norway (1000km distance to Northern Lights).

The NCCS work demonstrates that enabling 7 bar instead of 15 bar based shipping can significantly lower costs (**Figure 5**):

- Investment could be reduced by nearly 50%.
- Reduction in operating cost of 15%.
- Overall liquefaction and shipping cost would be reduced by 30%.

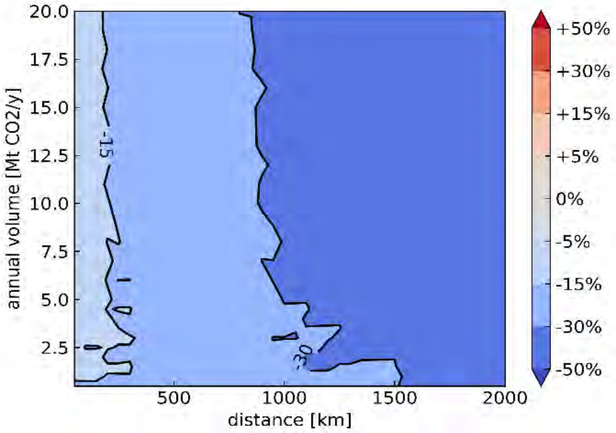

Figure 5. CO_2 conditioning and transport cost reduction achievable by 7 bar ship option compared to the 15 bar ship option (color code indicates cost reduction) [7]-[8].

Case 4 – Model enabling qualification of natural gas pipelines for CO_2 transportation

Main impact:

Reduced uncertainties in the design of new pipelines and re-qualification of existing ones improves safety, lower the costs and accelerates deployment of CCS.

The challenge:

CCS deployment requires a pipeline network for CO_2 transportation. Some natural gas (NG) pipelines are scheduled for decommissioning. Re-use of the NG pipelines for CO_2 transport requires qualification. One of the issues that need consideration is fracture propagation control, i.e., that a crack does not develop into a long, running ductile fracture (RDF). Existing engineering tools (Battelle two-curve method, BTCM) are not developed for CO_2 or modern steels.

The innovations:

The coupled FE-CFD model for assessment or running-ductile fracture (RDF), see [9]-[10], can significantly contribute, among other methods and measures, to re-qualifying existing NG pipelines for CO_2 transportation (**Figure 6**). The model is flexible and has a wider range of use than existing tools and would be expected to approve more reuse cases. It could lead to reduction of safety margins and hence reduced costs. It could contribute to a larger operational window.

The FE-CFD model can be used to develop a simpler-to-use RDF engineering tool.

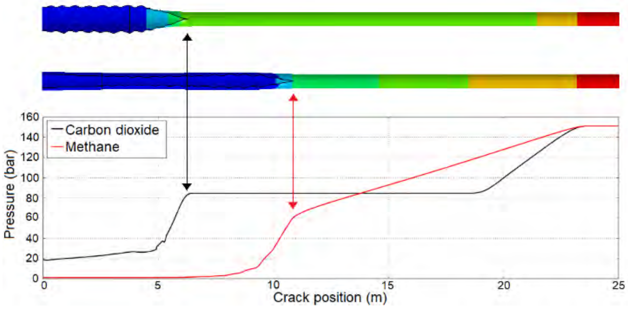

Figure 6. Example calculation showing that CO_2 gives a higher load on the opening pipe flaps compared to methane. Figure by G. Gruben.

Potential impact:

Base case for illustration: 200 km (offshore) pipeline is requalified for transporting 2.5 Mt/yr CO_2, assumptions relevant for DC2030.

Avoided costs and CO_2 emissions due-to re-qualification of existing natural gas pipeline to transportation of CO_2:

- Avoided investment cost according to Sepra et al [11] for a 200 km 12" offshore pipeline: 1.18 M€/km*200 km = 236 M€.
- Avoided CO_2 emissions by not having to produce and install the pipeline, calculated using iCCS [12]: 460 t/km * 200 km = 92 kt.

Case 5 – Innovative laboratory testing of cement to rock bonding in CO_2 injection wells

Main impact:

Innovative laboratory methodology for testing of cement to rock bonding, giving access to all needed strength values for correctly assessing a well integrity barrier.

The challenge:

Satisfactory sealing of the abandoned wells is mandatory and may limit the total injection volume or even disqualify a storage site, if not proven. Existing well construction and sealing (P&A) methods rely on Portland cement with additives or alternative materials, which are difficult to qualify and test. On average, primary cementing services constitute around 5% of well cost. Secondary cementing can result in an incremental increase of up to 20% of well cost [13]. In order to assess experimentally the performance of a well sealant, bulk as well as interface properties need to be correctly measured

[14]. Similarly, for predictive modelling purposes, strength values, both in shear and tension mode, are needed for cement bulk as well as interface with steel and with rock. These last properties were until now difficult to assess and seldom taken correctly into account in numerical models.

The innovations:

The testing method, developed in the laboratory, addresses several aspects needed to fully assess how a cement or other sealing material will perform at realistic down-hole conditions by performing thorough testing of the basic mechanical parameters needed for modelling purposes at field-relevant conditions. Several test methodologies have been developed, targeting both shear and tensile properties of cement bonding to rock. In addition, an ECCSEL rig is developed allowing to assess loss of cement bond in a field-relevant radial concentric geometry, including steel casing and surrounding rock (**Figure 7**).

Potential impact:

Less conservative models for cement integrity will reduce construction and maintenance costs and reduce demand for materials, and by this also reduce the CO_2 footprint. Testing at field relevant conditions also increases confidence in CO_2 storage.

<u>Base case for illustration</u>: 15-20 Mt/yr CO_2 is to be stored in NCCS DC-2030. The cost per ton of Portland cement is around 40 €/t. Additive pricing goes from 80 €/t for gypsum to 4000 €/t for fluid loss additives. Cementing corresponds to between 2-8 M€ per well. Assuming average optimal injection rate of 0.2 – 1 Mt/year per well, with optimized placement, one would need up to 100 wells to reach the DC 2030 scenario, with cement costs reaching up to 800 M€.

- 10 % less cement per well would lead to an economy of up to 80 M€.
- Additional 10 % cost reduction could be obtained by not having to use special cement additives.
- Plug and abandonment (P&A) needs for existing wells: 400 k€ per day * 30 days up = 12 M€ per well to plug (www.fourphase.com). Halving the required plug length compared to current regulation results in 1 day less per well, this sums up to 40 to 1200 M€ savings depending on number of wells, on top of the well construction cost reduction.

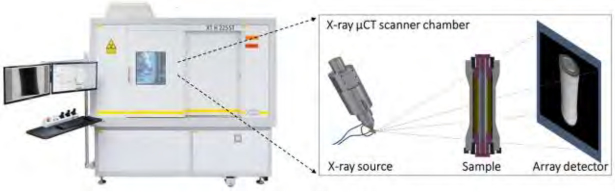

Figure 7. The ECCSEL well integrity research infrastructure. This mini-wellbore simulator is used for in-situ investigation of cement integrity under CT imaging. Sketch by A. Ghaderi.

<u>Case 6</u> – Novel methodology based on two-step Bayesian approach for quantitative CO_2 monitoring

Main impact:

Reduced monitoring costs, more predictable operation, improved safety, and support for communication with regulators and the public.

The challenge:

CO_2 monitoring is a regulatory requirement and an essential tool for predictable operation and safe CO_2 storage. While conventional monitoring focus mainly on determining the location and extent of the CO_2 plume, a more quantitative monitoring approach is useful for detailed conformance (agreement between observations and predictions) assessment and reliable operational decision making. A quantitative approach could also be used during the characterization phase to give more accurate assessment of storage capacity.

The innovations:

The Bayesian Rock Physics Inversion method developed and investigated in NCCS, in collaboration with the Pre-ACT project [15], is a two-step approach consisting of geophysical inversion followed by rock physics inversion with uncertainty propagation (**Figure 8**) [16]. The method allows quantification of the most relevant rock physics parameters including their uncertainties. It is, in particular, useful for discrimination between pressure and saturation changes in the reservoir. The method handles multiple types of geophysical input data and can take prior information (e.g., well logs or down-hole measurements) into account for reliable assessment of site performance.

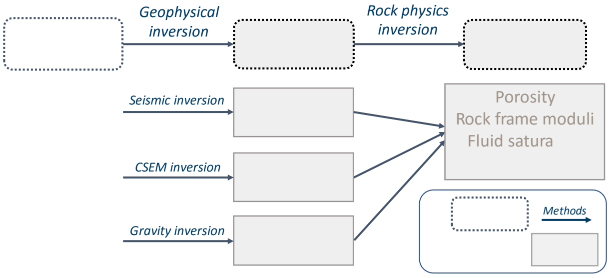

Figure 8. Two-step workflow combining geophysical and rock physics inversion. Figure by B. Dupuy, SINTEF.

Potential impact:

The two-step Bayesian approach for quantitative CO_2 monitoring contributes directly to more informed operational decisions, safer storage, and at the same time fewer costly interventions during CO_2 injection. In addition, the approach uses available data in an efficient way, which can help to reduce the need for frequent (costly) geophysical surveys. Any operator could profit from adapting such a workflow as part of their Measurement, Monitoring, and Verification (MMV) plans, for updates of their reservoir models, better forecasts, and improved decision making. The quantitative information, and especially the uncertainty assessments, may also be helpful for communication with other stakeholders and with the public.

Illustrative example: With more efficient use of acquired data, we assume that the interval between geophysical surveys can be increased by up to 25% and that every second or third survey can be sparser and more targeted. This could result in around 30% overall reduction of monitoring costs. For a storage project of Sleipner to Aurora size (DC2025) and 20 geophysical surveys at 10 M€ per survey, this means a potential cost reduction of around 60 M€. In addition, we foresee a reduction in risk of, and costs related to, unexpected events like temporary interruption of operation, unplanned well intervention, need for additional wells, or even early abandonment of the storage project.

3. Discussion and conclusions

Assessment of the possible impact of innovations which are currently at low TRL, is not an easy task and is typically based on different assumptions.

During the NCCS impact study, the following reflections were made:

- It is important to communicate that the quantitative estimates are not socio economic or business economic studies, but simplified calculations to demonstrate order of magnitudes.
- Transparent assumptions are essential to enable discussion of premises for the examples.
- Dialogue with industry is valuable to create realistic quantitative examples of potential impact.
- Mapping of qualitative and indirect effects is also useful but may be overlooked when quantitative examples are made.
- Many innovations build on outcomes from several research projects over many years.
- Innovations often represent one critical part of the CCS chain, and deployment will depend on implementation of the whole chain.

Nevertheless, this exercise helps to build a larger picture for the technology developers and show possible application and potential gains that industrial partners may have from implementing these innovations.

To contribute to the mitigation of climate change and limit temperature increase to 1.5°C per year, about 10 Gt CO$_2$ needs to be captured and stored annually. The NCCS impact study illustrates that novel methodologies and even incremental improvements in the technologies can contribute to significant cost reduction, improved safety opportunities for upscaling, thus accelerating full-scale CCS deployment.

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