



CLEAN ENERGY RESEARCH CENTRE PROFILE

The Norwegian CCS Research Centre (NCCS): facilitating industry-driven innovation for fast-track CCS deployment

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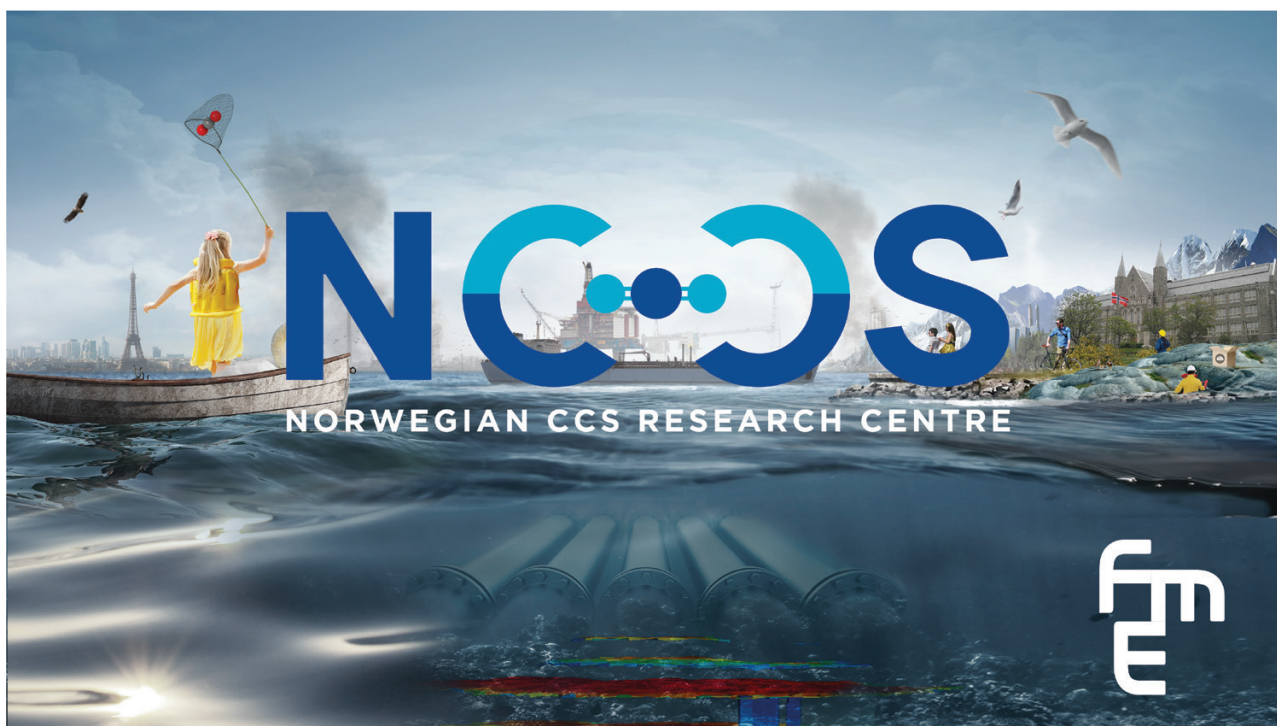
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Graphical Abstract



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Introduction

Centres of Excellence are long-term collaborative research entities that create synergism between the expertise of publicly funded research actors with strong industry direction. These centres are focused on strategic research of high relevance for the industry, while building the fundamental knowledge and competence to push the scientific forefront—a truly collaborative effort-critical mass of researchers, students and industry.

The Research Council of Norway has established a funding scheme and a portfolio of Centres for Environment-friendly Energy Research (FME programme). This programme was developed to advance expertise and promote innovation through a focus on long-term research in selected areas of environment-friendly energy, including renewable energy, energy efficiency, social sciences and CO₂ capture and storage (CCS). The main ambitions of these centres include:

- Encourage enterprises to innovate by placing stronger emphasis on long-term research and by making it attractive for enterprises that work on the international arena to establish R&D activities in Norway.
- Facilitate active alliances between innovative enterprises and prominent research groups.
- Promote the development of research groups that are at the cutting edge of international research and are part of strong international networks.
- Stimulate researcher training in fields of importance to the user partners and encourage the transfer of research-based knowledge and technology (https://www.forskningsradet.no/prognnett-energiserter/About_the_centres/1222932140914).

In the CO₂ CCS arena, the FME programme has supported two centres in the 2009–17 period. FME BIGCCS (www.bigccs.no) developed research-based innovations on CO₂ capture, CO₂ transport, CO₂ storage and the CCS value chain [1–3] and FME SUCCESS addressed research areas related to CO₂ storage in the subsurface (<http://www.fme-success.no>).

In 2016, the Norwegian CCS Research Centre (NCCS) was launched in the FME programme, coordinated by SINTEF Energy Research in Trondheim, Norway. NCCS includes a large CCS research community in Norway (primarily), Europe and the USA together with motivated and engaged industrial partners who will help guide the research towards industrial relevance. NCCS is an 8-year endeavour in which the core competence is built and knowledge transferred to the industry, promoting value creation through commercialization.

1 NCCS—vision, goals and objectives

NCCS (www.nccs.no) aims to fast-track CCS by working closely with the industry on research topics designed to address major barriers to CCS deployment in Norway, Europe and the world. Key words behind the rationale

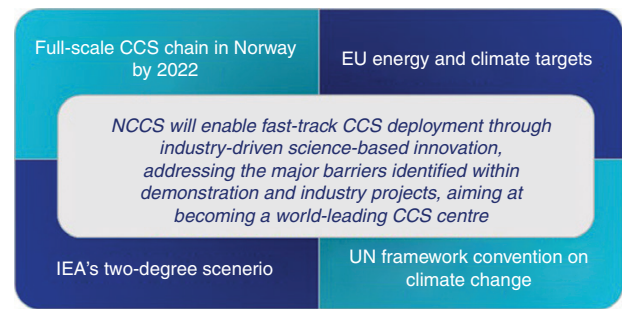


Fig. 1: NCCS's core vision (centre text) and rationale for the vision

for NCCS's vision extracted from the NCCS proposal submitted in 2015 are shown in Fig. 1.

NCCS research focuses on two 'CCS Deployment Cases': CCS for Norwegian Industry and Storing Europe's CO₂ in the North Sea. Researchers focus on tasks related to the CCS technologies for the Norwegian full-scale case and seek to find clever ways to integrate capture with transport, and with storage. As the first CCS projects will undoubtedly require public/private partnerships, any ways to reduce the cost of CCS will be a saving for each taxpayer. There is a huge potential in the North Sea to store CO₂ from all over Europe and NCCS will unlock this potential through dedicated research that has been pointed out by the industry as addressing key barriers.

1.1 NCCS: a world-class partnership

NCCS comprises international oil and gas companies, CCS technology vendors and technology users in the private and public domains. The research partnership consists of SINTEF, NTNU, University of Oslo (UiO), Norwegian Geological Institute (NGI) and other highly ranked research institutes and universities. As a world-class CCS centre, the partnership includes world-class scientists, state-of-the-art laboratories and research facilities, and advanced simulation tools that will be expanded and complemented in NCCS. Fig. 2 illustrates the collaborative structure of NCCS.

1.2 Overall objective

NCCS will enable fast-track CCS deployment through industry-driven science-based innovation, addressing the major barriers identified within demonstration and industry projects, aiming to become a world-leading CCS centre.

1.3 Focused on two industry-driven deployment cases

NCCS will provide consistent, targeted research in areas that will contribute most significantly to large-scale CCS deployment. NCCS industry partners have already agreed on two key deployment cases (Fig. 3), ensuring industrial ownership and governance of the centre and industrial relevance for the prioritized scientific tasks: (i) CCS for Norwegian

Industry capturing CO₂ from industrial sources in Norway and transporting it by ship for storage on the Norwegian continental shelf and (ii) *Storing Europe's CO₂ in the North Sea Basin* capturing CO₂ from a variety of sources in Europe and transporting it via a pipeline network to Norwegian storage sites. In this paper, the following aspects of how NCCS has been built and developed will be presented:

- Ensuring industry relevance.
- Ensuring research competitiveness.
- Promoting and facilitating innovation.
- Integrating education.
- Aligning international research.
- Communication and outreach.
- Interplay with the funding agency.

2 Ensuring industrial relevance

As an industry-driven Centre of Excellence, NCCS's activities are shaped by industrial engagement at both the



Fig. 2: The collaborative structure of NCCS

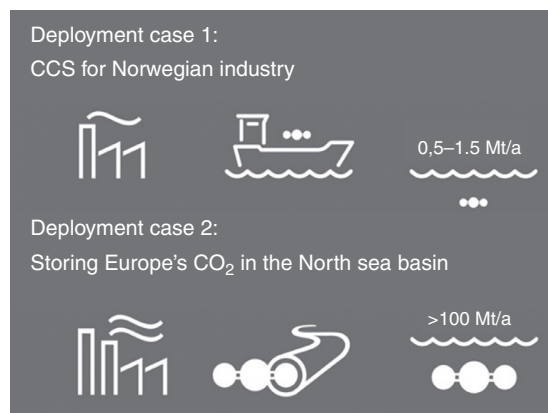


Fig. 3: Sketch of the NCCS deployment-case concepts

strategic and operational levels. The board is led by an industrial partner and has industry majority. In addition, a Technical Advisory Committee (TAC) has been established with representatives from all industrial partners and vendors in NCCS. Each R&D activity, or Task, has assembled a Task Family of researchers, students and industrial partners working together. Further descriptions of how NCCS ensures industrial relevance are outlined below.

2.1 Deployment-case concept

In the development of the NCCS FME proposal, the research and industry partners together defined two deployment cases to provide a context that enables consistent, targeted research in the areas that will contribute most significantly to accelerating large-scale CCS deployment:

Deployment case 1 (DC1): CCS for Norwegian Industry tackles challenges related to capturing CO₂ from variety of sources in Norway and transporting it for storage on the Norwegian continental shelf (NCS). DC1 is not identical to the Norwegian full-scale project but should as far as possible support and align with the project to realize the government's ambition to have the project operational in 2022 (estimated). In addition, DC1 aims to address sustainable CCS solutions for Norwegian stakeholders, beyond the Norwegian full-scale CCS project.

Deployment case 2 (DC2): Storing Europe's CO₂ in the North Sea Basin capturing CO₂ from a variety of sources in Europe and transporting it via a pipeline network and potentially ships to Norwegian storage sites. DC2 aims to outline the possible evolvement and structure of a European CCS chain, aligning with European CCS projects. Through science-based strategies for large-scale CCS deployment, DC2 shall support NCCS in identifying critical technical and legal barriers that should be addressed via targeted research.

The deployment cases are used both for prioritizing research areas to be included in NCCS and for directing research within each topic. In the operation of NCCS, the deployment-case concept has the potential to align research across disciplines and along the CCS chain while allowing strong industry ownership. Furthermore, the concept works well for communicating the research in NCCS to a wider audience. Further work is underway to develop the deployment concept, for example through a scenario study, to maximize the potential of this concept. Some research topics addressed by the 12 research tasks (shown schematically in Fig. 4) in NCCS are deployment-case-specific, but most topics are relevant for both deployment cases, depending on the context and the concerns related to a deployment-case-specific barrier.

2.2 Technical Advisory Committee

As an industry-driven research centre in the start-up phase, great effort has been made to create appropriate discussion

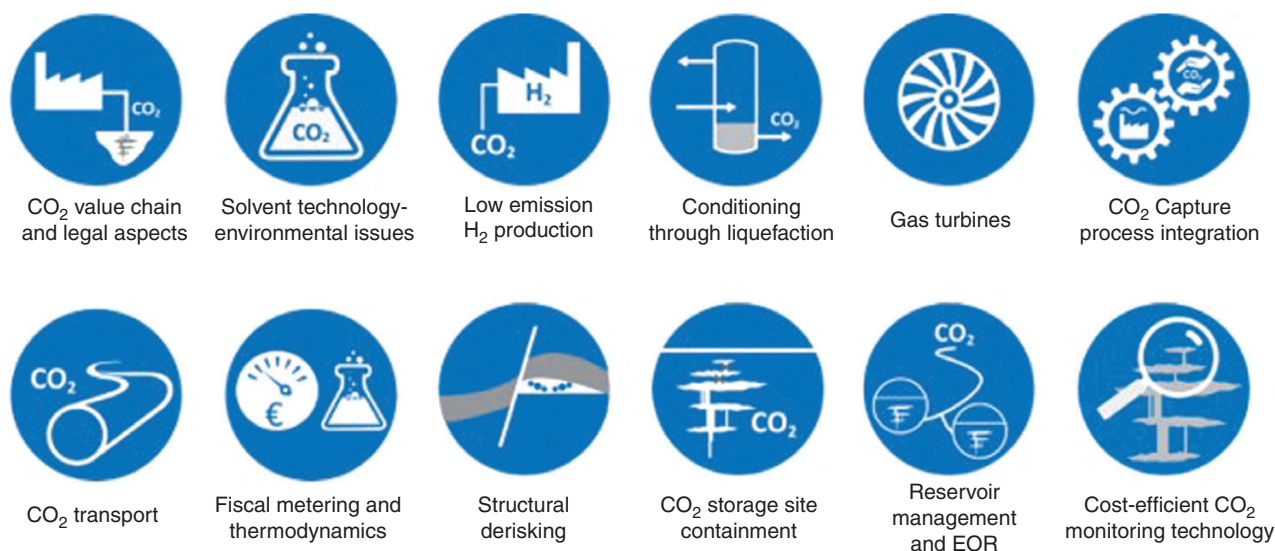


Fig. 4: Research tasks in the Norwegian CCS Research Centre (2019). For more information, see www.nccs.no.

forums and processes for cooperation with industry partners. An important and highly successful measure has been to establish ‘families’ in each R&D Task. The Task Families include specialists from industry and research actors with particular interest in the topics addressed. Through workshops and Skype meetings, all partners can contribute to technical discussions, discuss the results and develop the ambition for the following year’s work programme. All of NCCS’s industry partners have been active contributors in one or more Task Families, with many partners providing Task Family members for all of the tasks.

NCCS aims to be a dynamic centre addressing challenges of high relevance to industry. An important tool for this is the TAC, which was established in 2017. The committee consists of and is led by industry, and the purpose is to advise the Centre Director on strategic choices of direction and prioritization of topics in the portfolio of research activities.

2.3 Tackling partner-specific R&D challenges in a consortium

NCCS is a consortium with different categories of partners, as illustrated in Fig. 2. Oil and gas companies have a long-term strategy towards CCS and will likely purchase technology one day. They have different research questions from, for example, a vendor who is currently developing technology to sell on the market in the future. NCCS is a precompetitive research partnership, meaning that the R&D is at an early enough stage such that even competitors can work towards solving problems of collective interest. The partners share a common knowledge base and together in NCCS build competence networks with value often beyond CCS R&D. Selected collaborations within NCCS are outlined below to illustrate the various constellations of tackling partner-specific topics in the R&D portfolio.

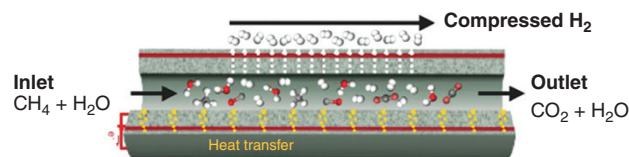


Fig. 5: Single tubular segment of the protonic membrane reformer for production of compressed H_2 by steam-reforming and water-gas shift. Scanning electron micrographs show close-up of the membrane electrolyte and electrodes [4]. Published with permission of Springer Nature.

2.3.1 Example 1: low-emission hydrogen production

Fig. 5 illustrates the Protonic Membrane Reformer (PMR), pre-combustion CCS technology being developed by NCCS partner CoorsTek Membrane Sciences [4]. As an overall goal, the work in NCCS aims to identify and improve material stability and performance issues of the ceramic membrane and seals under PMR operating conditions and thermal cycling. A membrane unit at SINTEF was upgraded for testing of electrochemical membranes provided by CoorsTek and commissioned for PMR test conditions (800°C and 10-bar pressure with a steam to carbon ratio of 2.5). A single-segment tubular membrane was tested under PMR conditions and further improvements were made to the set-up. Through work in NCCS and complementary projects, SINTEF Industry recently published a study on the interaction between CO_2 molecules and the surface of $BaZrO_3$ —a membrane material utilized in electrochemical membrane reactors for hydrogen production from natural gas [5].

2.3.2 Example 2: hydrogen combustion in gas turbines

Low-carbon-footprint H_2 (e.g. produced from natural gas with CO_2 capture and storage via electrolysis) can reduce CO_2 emissions and provide an energy-storage solution to balance non-dispatchable renewable-energy resources.

In NCCS, vendor-focused R&D within the NTNU/SINTEF/Ansaldo collaboration is addressing how gas turbines can be designed to burn H_2 and H_2 mixtures. In this task, researchers, students and industry are working closely together to gain fundamental insight into the hydrogen–air combustion processes in a model combustor to further develop Ansaldo Energia’s GT26/GT36 sequential combustor design using three-dimensional direct numerical simulation, detailed chemical kinetics and chemical explosive modes analysis. An example illustration from their recent work on turbulent reactive flow is shown in Fig. 6, republished with permission from [6]. This task illustrates a vendor-driven R&D activity, with tight integration of Ph.D. students tackling fundamental research questions asked by a high-tech company.

2.3.3 Example 3: structural de-risking

The Northern Lights project is based in an industry partnership that facilitates the Norwegian government’s demonstration project ‘Full-scale CO_2 handling chain in Norway’. Northern Lights includes transport, receiving, injection and permanent storage of CO_2 in a geological reservoir in the northern part of the North Sea <https://www.equinor.com/en/how-and-why/impact-assessments/northernlights.html>.

Selected NCCS Research Tasks are actively involved in the Northern Lights project, by tackling current R&D challenges and preparing for large-scale CO_2 storage in the future. One example is where the NGI and the UiO are working on how to reduce the risks related to fault integrity and sandstone distribution through detailed mapping, by providing data sets and discussions that forward Northern Lights work [7, 8]. By that, NCCS supports the work to increase the storage capacity on the NCS and will provide additional confidence for large-scale CO_2 storage offshore. In addition, CO_2 -monitoring techniques, including developing rock-physics models to determine CO_2 for storage at the Sleipner field, have been in focus in NCCS [9, 10].

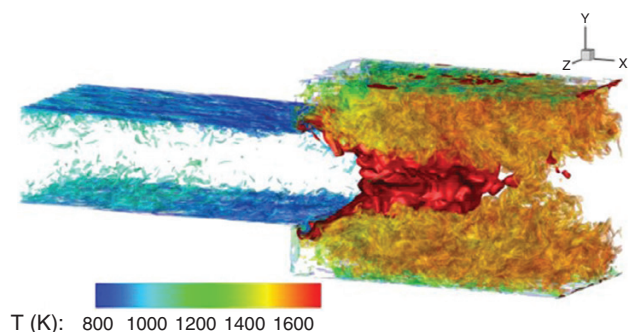


Fig. 6: Qualitative illustration of the turbulent reactive flow in Ansaldo’s reheat combustion chamber. Turbulence structures are coloured by the local fluid temperature; the flame is represented by the red surface [6]. Published with permission of Elsevier.

2.3.4 Example 4: fiscal metering of CO_2

Fiscal metering is the measurement of a quantity of product involved in a commercial transaction. The EU ETS (Directive 2003/87/EC) (<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003L0087>) creates the commercial environment for fiscal metering of CO_2 and defines the maximum uncertainty in the measurement and delivery of CO_2 . The use of fiscal meters eases the burden on users when calculating uncertainty but, to our knowledge, no metering technology has been verified with CO_2 at the accuracy required by the ETS at full-scale flow rates. The fiscal metering activity in NCCS will provide valuable support and is in line with the overall innovation objective of the centre. KROHNE is a world-leading manufacturer and supplier of solutions in industrial-process instrumentation and is crucial to the success of this research activity. As a producer of both ultrasonic and Coriolis meters, KROHNE will be in a position to answer many of the current gaps listed above and may point in the right direction on others.

3 Ensuring research competitiveness

3.1 Dynamic and flexible research profile

NCCS implements methods to evaluate the R&D profile to maintain research competitiveness and align with industry throughout the centre’s lifetime. NCCS has the ambition to be dynamic and is readily suited to shift scientific focus to adapt to the CCS world as it changes and develops. The scientific tasks are assessed and reviewed yearly, and corrective actions and improvements are implemented when needed. NCCS can use this method to evaluate the R&D profile regularly to maintain research competitiveness, and to align with the CCS world. This is done by taking the learning and needs from large-scale and demonstration projects (e.g. the Norwegian full-scale CCS chain) and adapting the R&D direction accordingly, based on feedback from the industrial partners.

The R&D profile is regularly reviewed, considering guidance from the TAC, progress towards fulfilling the success criteria as outlined by the Research Council of Norway (see Section 8) and achievements of milestones, deliverables and publications. When new R&D topics are requested by the industrial partners, it is possible to adjust the R&D profile through a variety of mechanisms. One example is to apply for additional projects that can be amended to the consortium agreement. In 2018 and 2019, seven additional competence-building R&D projects were added to NCCS. If an R&D project is requested that would require different funding mechanisms (e.g. the topic has increased intellectual-property (IP) concerns), it may require a different type of R&D activity than can be included in NCCS. Nevertheless, the close constellation of industry and research partners enables the R&D forefront to be pushed, innovations to be generated and technologies to be brought closer to realization.

3.2 Advisory groups in NCCS

In addition to the TAC described in Section 2.2, NCCS has two additional groups assembled to ensure the research competitiveness and proper direction of the centre. The NCCS Special Advisory Group (SAG) was established to provide NCCS guidance on strategic issues, such as trends and new developments in CCS, and to help position the centre globally. The 10 members of the SAG were selected based on their positions worldwide within CC and is led by Dr Nils Røkke, currently the chairman of the European Energy Research Alliance.

The NCCS Scientific Committee is an advisory committee with leading international academic capabilities giving guidance to the centre towards scientific progress. The Scientific Committee comprises primarily high-ranking scholars in Europe, North America and Asia, and will provide strategic advice on scientific focus and priorities and evaluate the output of the centre, primarily in terms of journal articles, and evaluate the impacts on the scientific forefront of the various disciplines.

4 Promoting innovation in NCCS

NCCS's 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 cooperation between scientists and industry partners. The potential for spin-offs, start-ups or license agreements will be continuously monitored. As an international CCS research hub, NCCS is built to promote open innovation processes [11]: companies involved in the centre will be able to commercialize ideas and emerging technology 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 borders 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. Innovation may be defined as a product, a technology, a component, a process, a model, a concept, an experimental facility or a service that is new or significantly improved with respect to properties, technical specifications or ease of use. This gives many potential routes for commercialization—from a single actor, via joint venture, to broad implementation for several stakeholders or markets. Thus, commercialization following the open innovation model requires a comprehensive IP strategy to maximize value creation for each involved company. NCCS will aim to disseminate results among partners whenever possible and, at the same time, secure IP rights for each partner where necessary.

NCCS maintains a continuous focus on innovation and technology transfer from NCCS. A dedicated Innovation and Technology Transfer task intends to be an enabler within the centre, striving to promote a good environment for developing innovations through engaged cooperation

between researchers and industry partners on specific topics. The task essentially has five defined roles within the centre:

- *Reminder*: Continuous focus on reminding the researchers and the scientific tasks to consider the potential for innovation and encouraging the tasks to think outside the box when planning and conducting their research.
- *Facilitator*: Contribute to good and engaged cooperation between researchers and industry partners. This will be done both on a day-by-day basis through interaction with Task Families and individual partners and on a strategic level through influencing annual working plans. In addition, dedicated workshops, meetings or other virtual arenas are designed for promoting concrete collaboration within the centre.
- *Identifier*: Through interaction with the tasks; help with identifying, describing and categorizing innovations; or research with high potential for becoming or contributing to innovations.
- *Supporter*: Contribute with knowledge and support for intellectual asset (IAM) and IP management within and outside NCCS, through patenting, licensing, strategies for spin-offs or start-ups, etc., in concert with the Technology Transfer offices of both SINTEF, NTNU and UiO, as well as other relevant actors within the field. Also categorizing and reporting identified IP within NCCS.
- *Communicator*: Communicate original research, promising results as well as potentials for innovation to partners within NCCS, stakeholders outside the centre and the general public. Communication shall be within the boundaries set by the consortium agreement and the strategy for IP management.

Through these five roles, the Innovation and Technology Transfer task aims to become a significant resource for all partners within the centre.

4.1 The Innovation Management Pathway

In 2017, a case study of innovation management in six of the eight first Centres of Environmentally Friendly Energy Research in Norway were conducted. This work resulted in both a master's thesis [12] and the establishment of a methodology dubbed the Innovation Management Pathway shown in Fig. 7. This is a shortlist of nine ambitions the centre management should live by to be able to promote innovative output from the research collaboration in the centre. Now, this methodology is becoming a key part of the NCCS Innovation Framework. From this work, the following recommendations were given to NCCS in order to maximize the innovation potential of the research.

- *Innovation structures*: Formal structures as innovation committees and reporting mechanisms for innovation will indirectly promote a culture for innovation and innovative research, given continuous attention and focus from management to the topic over time.

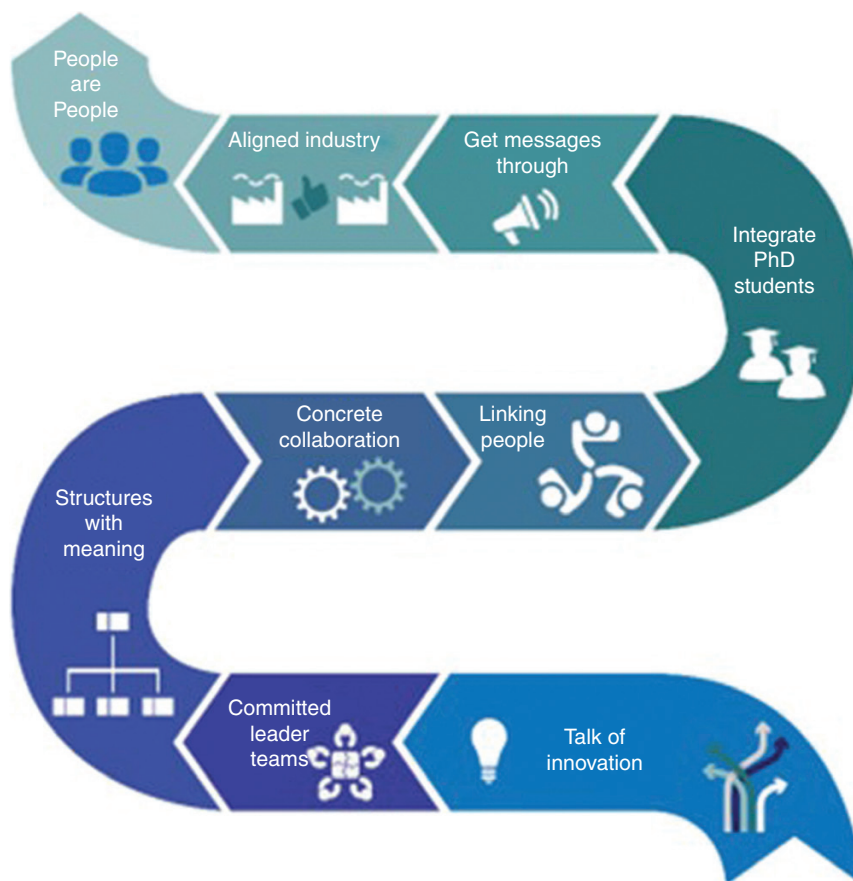


Fig. 7: Illustration of the Innovation Management Pathway—a methodology developed in conjunction with NCCS for promoting innovative output from the centre.

- *Relationships*: Engaged relationships between university and industry through high relational involvement and developed cooperation will contribute towards increasing understanding and promoting innovation and innovative research, whereas absence of relational involvement from industry can counteract innovation and innovation processes in research collaborations.
- *Engagement versus relationships*: Industry engagement towards a research programme will not alone promote innovation to the same extent as high relational involvement and concrete collaborations will.
- *Enabling relationships*: The research manager can be a key enabler for engaged relationships by acting as a knowledge broker and bridge builder within the research programme, whereas failing at this can counteract innovation processes.
- *Linking people*: By facilitating close links between researchers and their peers amongst the industry partners, the research manager will contribute to increased understanding through bridging opposing logics throughout the research programme, and hence promoting development of relationships.
- *Cooperation between industries*: Limited direct cooperation between competitors within research programmes disables industry partners to reap the intended benefits from competition, while still exposing them to the

potential downsides as weak forms of trust and fear of opportunistic behaviour.

- *Leadership roles (as the team player)*: For promoting innovation from different stakeholders within the research programme, the research manager needs to take on varying leadership roles that address the needs of the specific stakeholder group. Mixing or ignoring these leadership roles will induce frustration and counteract innovation within the research programme.

4.2 Can we quantify effects of innovations in CCS research?

Quantification of potential effects of CCS innovation is challenging but, at the same time, it is very important in order to justify the research investments. In general, research is often co-funded by public and private actors. In research for tackling challenges related to energy and greenhouse-gas emissions, the role of the authorities in promoting and funding research, development and education has been crucial. Over the last 10 years, Norwegian CCS research co-funded by public funding programmes and private actors amounts to about 250 million € (www.climit.no; https://www.forskningradet.no/prognett-energiserter/About_the_centres/1222932140914). It is pertinent to shed light on whether this is the best way to spend limited

funds. To evaluate the effects of research investments, it is essential to identify the most important results and innovations and quantify the potential effects of putting new technologies and solutions into use. When it comes to CCS, this is a task that is extraordinarily challenging, as there is as yet no market for CO₂ management and therefore no market for CCS technologies. However, a Norwegian study is currently being conducted to identify and, as far as possible, quantify the effects of energy research. CCS research is one of the areas addressed.

To provide an indication of the potential value of CCS research investments, seven selected innovations from NCCS and its predecessor BIGCCS are investigated to estimate potentials for cost reductions if the new innovations are successfully implemented in one full-scale CCS project. To enable some degree of quantification, assumptions had to be made for each topic, for example regarding the current cost of material, equipment and operations. However, the study aims to make the assumptions as transparent as possible to allow discussion on their realism. Based on scenarios for CCS deployment developed from IEA and UN IPCC scenarios, it can be shown that the potential value creation from estimated cost reductions alone by far exceeds the investments in the two research centres [13]. Effects from possible commercialization and qualitative effects related to aspects such as safety and environment come in addition and are not considered in the quantification. A prime motivation for the study is to initiate a broader discussion that goes beyond the anticipated costs of CCS addressing also the potential gains and opportunities for business development.

4.3 Managing IP

According to the NCCS Consortium Agreement, each participant in NCCS owns its own background IP and project results, but each participant has user rights to others' background and project results when this is necessary for them to implement their own work in the centre or when this is necessary for them to utilize their own work in the centre commercially. Each participant is required by the Consortium Agreement to protect project results capable of industrial or commercial application.

To be able to follow up on IP management on a day-to-day basis, an IP Guide has been developed in NCCS, tailored for the centre. The ambition for the guide is to help the researchers navigate better and safely in the IP landscape, and thereby make qualified decisions together with the NCCS industrial partners. The Innovation and Technology Transfer task is responsible for IP management overall in the centre (thus, each partner owns their own results and thereby has the right to make individual decisions regarding use and exploitation of results) and work as consultants for the researchers and the consortium on the matter whenever necessary.

5 Role of academia in an industry-driven Centre of Excellence

Educating the next generation of CCS experts is a crucial piece of the innovation puzzle. Even for technologies at a high technology readiness level (TRL), fundamental research can provide the knowledge needed to push technology even further. One of the most important ambitions of NCCS is to educate master's and doctoral students in CCS research so that they can continue apply their learning to advance CCS, whether they work in industry, as researchers or in the political arena. Centres of Excellence provide the stability of long-term R&D to enable students to complete their degrees, with active engagement from industry. The students are integrated into the Task Families and are encouraged to communicate and disseminate in interdisciplinary forums. Joint specification of master's and Ph.D. students by universities and industry can not only provide opportunities for value creation for industry, but students are motivated by potential job prospects. This also helps to balance the, at times, diverging goals of academic excellence versus the shorter-term industrial perspectives, both of which are crucial success criteria for a Centre of Excellence. NCCS plans to educate more than 20 Ph.D. students in addition to 60+ master's students, summer students and exchange students.

5.1 CCS Summer School

NCCS hosted the 12th IEAGHG CCS Summer School (<https://ieaghg.org/summer-school>) in Trondheim in 2018, with 58 students from 24 countries. This year, in addition to covering all aspects of CCS in lectures (presented by leading international experts), the students also had group exercises in communication, designing monitoring plans, interactive careers sessions and group project work with presentations; NCCS added to the programme with very up-to-date information on the development of the new Norwegian storage site and the industrial sources of CO₂, representing state-of-the-art work-in-progress information by a leading CCS country.

6 Aligning international research

Active participation in organizations spearheading the strategic CCS development on the European arena is a priority for NCCS and contributes in the stage-setting of the research agenda in the field of CCS. As already mentioned, Dr Nils Røkke is the chairman of the European Energy Research Alliance (EERA). With 175 research centres and university members from 27 countries, EERA's objective is to build on national and European research initiatives and to be at the cornerstone in the European Strategic Energy Technology Plan (SET Plan). NCCS is active in the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP)—a coalition of stakeholders united in their support for CO₂ capture and storage as a key technology for combating climate

change. ZEP serves as adviser to the European Commission on the research, demonstration and deployment of CCS. The CCS Joint Programme under the EERA (EERA JP-CCS) is coordinated by SAG member Dr Marie Bysveen. EERA JP-CCS is an authority on CCS research, development and innovation, and coordinates national and European R&I programmes to maximize synergies and facilitate knowledge-sharing to accelerate the development of CCS. Participants in NCCS have been active in FP6 and FP7 EU projects, are involved in ongoing H2020 projects and are leading and/or active in five ACT-ERA-Net Co-fund projects that started in 2017.

NCCS has taken a role in the Memorandum of Understanding between the US Department of Energy and the Ministry of Petroleum and Energy in Norway through collaboration with American National Laboratories, universities and industries while supporting the Norwegian Secretariat (RCN) in networking events and seminars.

6.1 International research and experimental infrastructure

Experimental facilities for developing and testing CCS technologies are a key component of moving up the TRL. To provide a pan-European distributed research infrastructure for capture, transport and storage, the European Carbon Dioxide Capture and Storage Laboratory Infrastructure (ECCSEL) was launched in 2008 and became a legal entity as a European Research Infrastructure Consortium in 2017.

The mission of ECCSEL is opening up access for researchers to a European research infrastructure devoted to second- and third-generation CCS technologies in an efficient and structured way to help enable low to zero CO₂ emissions from industry and power generation to combat global climate change (www.eccsel.no). As an integrated, European research infrastructure, ECCSEL combines and supports the construction and upgrading of the best research facilities in Europe for CCS. Today, there are more than 54 world-class research facilities across Europe. More than half of the R&D activity in NCCS is currently utilizing ECCSEL infrastructure, and additional laboratory facilities are in the planning or construction phase [14–16].

6.2 Researcher mobility

Mobility of personnel in a large programme like a Centre of Excellence can be a catalyst for innovation, networking, knowledge-sharing and dissemination that cannot be done remotely. Therefore, NCCS has a dedicated mobility programme to encourage and fund such stays. Researchers and students are encouraged to spend time at partner institutes both within NCCS and with sister organizations around the world.

7 Communication and outreach

The NCCS communication plan has been developed to ensure the regularity and quality of communication efforts

of a centre with many actors and numerous research disciplines. Communication is crucial to ensure that NCCS results are communicated, that innovations are visible and that the level of awareness and knowledge about CCS is constantly increasing. Through sharing and visibility, the NCCS partners will make a global impact. CCS deployment requires industrial and political willingness as well as public acceptance. Communication will extend beyond the NCCS consortium and scientific community to promote innovations to industry and ensure that we provide knowledge and premises for public debate and policy development.

The NCCS communication method of results dissemination is as follows:

- All tasks in NCCS are responsible for communicating their results to partners, the research community and the general population.
- All innovations and every scientific article shall be popularized for a larger audience.
- NCCS offers tailored communication training for Ph.D. students, researchers and management.

7.1 Communication channels in NCCS

Peer-reviewed journal articles are the most widely used channel for disseminating research results. However, NCCS also popularizes all scientific articles, first in the form of a blog and then potentially into a more formal popular science article or, in special cases, a newspaper article. Blogs are published on the NCCS website (www.nccs.no) and newsletters are sent to subscribers regularly. Annual reports are produced and available on the website (<https://www.sintef.no/projectweb/nccs/annual-report-2017/>).

In addition to research partners presenting results at topic-specific international conferences, each year, NCCS holds ‘NCCS Consortium Days’—multiple-day events where results are presented and workshops are held to shape the follow-up work. NCCS also takes the leadership role in organizing the Trondheim CCS Conference, held every other year.

7.2 The role of social media in promoting R&D and innovation

In the twenty-first century, social media has emerged as a platform also to promote research and to reach industry, technology developers and the research community. Social media is a valuable tool to spread information related to current world trends, for example related to the need for CCS. Recent findings illustrate that social media assists in promoting the latest R&D results, develops contacts and is apt for creating awareness of research activities and results [17]. By being active in posting content and contributing to debates and discussions, researchers and industry can gain visibility and boost individual reputations as well as the reputation of NCCS. The

combination of communication platforms NCCS utilizes provides a multitude of arenas for disseminating results. However, it should be mentioned that researchers typically have the principle that anything published should be as accurate as possible and having something new and important to say does not always fit well with the essence of social media, where swift presence and reactions may be most critical [17].

8 Interplay with the funding agency

As the main funder of NCCS, the Norwegian State (through the FME programme of the Research Council of Norway) has a responsibility to safeguard high-quality performance and best value for the public money. The FME programme sets our clear conditions for support through contracts and definitions of the success criteria for NCCS (see Fig. 8). Through regular reviews, the RCN ensures NCCS maintains a longer and more strategic view, is the CCS R&D hub in Norway and evaluates whether NCCS is achieving its goals. The goals of the reviews are:

Primary evaluation: to identify and mitigate issues related to the establishment of the centre, the communication/collaboration of the large consortium and the potential impact of the R&D portfolio.

Interim evaluations: to gauge partner satisfaction, achievement of milestones/deliverables and value of scientific outputs, and provide feedback on major changes needed after a mid-way evaluation.

Final evaluation: evaluates the extent knowledge transfer to industry partners and summary of the wider impact of the R&D.

9 Conclusions

The NCCS is an international Centre for Environment-friendly Energy Research addressing CO₂ CCS—key technology in the portfolio of measures instrumental in all energy scenarios outlining conceivable paths to curb global warming.

This paper has outlined the process of developing and implementing NCCS, as a Centre of Excellence in the early phases of operation, and provided examples of how an industry-driven Centre of Excellence can become an innovation platform. NCCS aims to deliver science and technology that can unlock the potential of fast-tracking large-scale CCS. To achieve this, NCCS has focused on:

- Ensuring industrial relevance through tight integration of the researchers, industry partners and students in Task Families and having proper governance structures in place to allow adjusting the R&D profile based on industrial perspectives. In addition, research areas with partner-specific R&D challenges are handled in various ways to guarantee that goals and expectations are met.
- Ensuring research competitiveness through regular evaluation of the R&D profile and the desire to be as dynamic and flexible as possible when it comes to new ideas and promising innovative pathways. Advisory groups are employed to provide guidance and evaluations on the scientific quality of the results and to keep NCCS aware of broader trends and perspectives within CCS.
- Promoting and facilitating innovation through continuous focus on innovation and technology transfer from NCCS. A dedicated Innovation and Technology Transfer task will be an enabler within the centre,

NCCS Success Criteria	
Research activities <ul style="list-style-type: none"> • Production of doctorates • Scientific publications • Papers for presentation at high-level international conferences • Recognitions (awards, keynote lectures, invited articles) • Genuine cooperation between research partners 	Researcher training and recruitment <ul style="list-style-type: none"> • Effective framework for researcher training • Actively engaged in researcher training, especially at master's level • Increased recruitment of woman
Internationalization <ul style="list-style-type: none"> • Distinct profile and articulated objectives for international cooperation • Successful international research cooperation (EU projects) • Active collaboration with international research groups • Internationalization of Norwegian research, business and industry • The centre attracts outstanding international researchers • Centre researchers stay at institutions abroad 	Organization <ul style="list-style-type: none"> • Visible profile, strong identity and successful collaboration between partners • Organization well adapted to host institution • Board and management following up intentions • Common administration with scientific and administrative autonomy • Satisfactory gender balance
Innovation and value creation <ul style="list-style-type: none"> • Generate potential for innovation and enhanced partner competitiveness • Ramifications for society beyond that of the partners • Mobility between centre and use partners (both ways) • Research activities that are relevant for the partners • Effective transfer of results to the partners • Establishment of new research-based enterprises 	Partners and funding <ul style="list-style-type: none"> • Host institution and partners have increased their funding (beyond minimum requirements) • Efforts to attract new user partners • Successful in securing other external funding

Fig. 8: Key success criteria, derived from the contract between the Research Council of Norway and the Centres of Environmentally Friendly Energy Research

striving to promote a good environment for developing innovations through engaged cooperation between researchers and industry partners on specific topics.

- Integrating a strong educational programme in which students are tightly linked to the researchers and industrial partners and the security of a long-term programme is balanced with the (often) shorter-term perspectives of industry.

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Conflict of Interest

None declared.

References

- [1] Mølnvik MJ, Aarli R, Henriksen PP, et al. BIGCCS Innovations—Measures to accelerate CCS deployment. *Energy Procedia* 2016, 86, 79–89.
- [2] Mølnvik MJ, Aarli R, Røkke NA. BIGCCS centre-supporting large-scale CCS implementation. *Energy Procedia* 2013, 37, 6544–52.
- [3] Mølnvik MJ, Tangen G, Aarli R, Røkke NA. BIGCCS Centre—Boosting CCS research and innovation. *Energy Procedia* 2011, 4, 6133–40.
- [4] Malerød-Fjeld H, Clark D, Yuste-Tirados I, et al. Thermo-electrochemical production of compressed hydrogen from methane with near-zero energy loss. *Nat Energy* 2017, 2, 923–31.
- [5] Polfus JM, Yildiz B, Tuller HL, Bredesen R. Adsorption of CO₂ and facile carbonate formation on BaZrO₃ surfaces. *J Phys Chem C* 2018, 122, 307–14.
- [6] Aditya K, Gruber A, Xu C, et al. 2019. Direct numerical simulation of flame stabilization assisted by autoignition in a reheat gas turbine combustor. *Proc Combust Inst* 2019, 37, 2635–42.
- [7] Midtkandal I, Sundal A, Braathen A, et al. Project summary: CO₂ seal bypass—a multidisciplinary approach to CO₂ migration and storage. In: *14th Greenhouse Gas Control Technologies Conference*, Melbourne, Australia, 21–26 October 2018, 2–26.
- [8] Skurtveit E, Choi JC, Mulrooney M, et al. 3D fault integrity screening for smeaheia CO₂ injection site. In: *14th Greenhouse Gas Control Technologies Conference*, Melbourne, Australia, 21–26 October 2018, 21–26.
- [9] Dupuy B, Romdhane A, Eliasson P, et al. Quantitative seismic characterization of CO₂ at the Sleipner storage site, North Sea. *Interpretation* 2017; 5, SS23–42.
- [10] Dupuy B, Ghaderi A, Querendez E, Mezyk M. Constrained AVO for CO₂ storage monitoring at Sleipner. *Energy Procedia* 2017, 114, 3927–36.
- [11] Bogers M, Chesbrough H, Moedas C. Open innovation: research, practices, and policies. *California Manage Rev* 2018; 60:5–16.
- [12] Størset SØ. Managing open innovation processes in large university-industry research programmes—a case study from the Norwegian energy sector. In: *Department of Industrial Economics and Technology Management*. Trondheim: Norwegian University of Science and Technology, 2017.
- [13] Størset SØ, Tangen G, Berstad D, et al. Profiting from CCS innovations: A study to measure potential value creation from CCS research and development. *Int J Greenhouse Gas Con* 2019, 83, 208–15.
- [14] Grønli M, Lilliestråle A, Bredesen A, et al. ECCSEL—European carbon dioxide capture and storage laboratory infrastructure. *Energy Procedia* 2011, 4, 6168–73.
- [15] Quale S, Bolland O, Grønli M, Rohling V. ECCSEL—International laboratory infrastructure for CCS research, education and innovation. *Energy Procedia* 2017, 114, 7276–94.
- [16] Quale S, Røkke NA. Open access to world-class research facilities: The European CCS Laboratory Infrastructure, ECCSEL. *Energy Procedia* 2014, 63, 8069–96.
- [17] Jaring P, Back A. How researchers use social media to promote their research and network with industry. *Techn Innov Manag Rev* 2017; 7:32–9.