BUILDING NORDIC EXCELLENCE IN CCS

NORDICCS – THE NORDIC CCS COMPETENCE CENTRE

Top-level Research Initiative

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NORDICCS – The Nordic CCS Competence Centre

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Building Nordic Excellence in CCS
NORDICCS – The Nordic CCS Competence Centre

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nordiccs
Nordic CCS Competence Centre

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Message from the Director

It has actually come to an end, NORDICCS – the Nordic CCS competence centre. It was established four year ago during really hard times for CCS in order to address Pan-Nordic issues in CCS.

Typical questions raised were; Where can we store CO_2 in the Nordic countries, what is the most efficient way of transporting CO_2 in our region and which capture technologies are best suited to the oil and gas, power and industrial processes that can be found in these five countries? We pursued industrial cases, notwithstanding the territorial borders and to think as a region with common goals and opportunities. What is the business case for CCS here and what are the opportunities for technology development and innovation, which are the barriers – not only the technical barriers but also the legal and civic society barriers? Our ambitions were high and encompassed in a Nordic team feeling- we can do this.

NORDICCS key outcomes
I am proud on behalf of the team to say that we have over-achieved our targets. Our website contains a wealth of information for decision makers and other stakeholders to use. Let me draw your to attention some key outcomes:

- The NORDICCS storage atlas, a web based storage atlas for our region. Our best knowledge has been used to produce a comprehensive view of where storage is possible as well as estimated capacities. Also, we have a fully transparent methodology to assess the storage capacities- we have benefitted from close co-operation with the state authorities in order to get access to data and to use an agreed methodology. Surprisingly, Iceland has vast envisaged capacity to store CO_2 in young basalts, a storage capacity which could be on the same order of magnitude as the North Sea basin. The real capacity is tested in the CARBFIX project at Iceland, and valuable information has been gathered from this pilot plant operation.

- Clusters of transportation showing that a mix of "trunklines" and ship transport is the best way of doing this. Hubs will become important and we have identified where these could be located and which source sink combinations we can foresee. It is clear that ship transport will be the preferred choice of transport for many plants in the Nordics, due to large distances and volumes too low to justify pipelines.

- Capture technologies- and combined capture and storage. The Icelandic case, storing CO_2 from geothermal wells, is a ground breaking project that NORDICCS has been lucky to become a part of- and to utilize those facilities provided so kindly by our industrial partners.

- Understanding what role CCS could play in the Nordic region energy and climate policy. This is embedded in our reference document, The Nordic CCS roadmap. This binds everything together – where we can capture, how we can transport and where we can store and to what cost. It is truly a document that will be a reference for the shaping of the Nordic energy and climate policy.

- Team and capacity building and dissemination. We have a Nordic team of excellence in CCS that will have long lasting effects. We have embedded PhD studies and two NORDIC Summer Schools, which have educated more than 60 young researchers, PhD and Post Docs in CCS. The summer schools are academic courses which also yield credits. Clearly this is a lasting footprint,

Nils A. Røkke, SINTEF Executive Vice President Sustainability, Photo: NordForsk/Terje Heiestad

and they have also contributed to the Roadmap activity in NORDICCS. The summer schools will be maintained in the future, given financial support can be found. Furthermore, NORDICCS arranged the parliamentarian side event at the 65th Nordic Council meeting in the Norwegian Storting in 2013 as well as a number of public events in all the Nordic countries. NORDICCS results are now requested in major European programs to understand how Europe can establish transport and storage for CO_2.

- Last but not least we presented NORDICCS at the COP21 in Paris – with a more global audience and interesting discussion. Nordic cooperation is also embraced by the IEA as an example of how regions can play a role in the climate mitigation issues.

As you see NORDICCS has over fulfilled our expectations and represents a solid case for further work and policy making. The team is eager to explore a continuation of this unique Nordic co-operation in CCS, and we hope there will be funding instruments to allow for this to happen. Building a Nordic team of excellence in CCS is no small feat and we should strive to maintain this momentum for the benefit of the region's energy and climate strategy and policy.

Nils A. Røkke
Director, NORDICCS

Executive summary

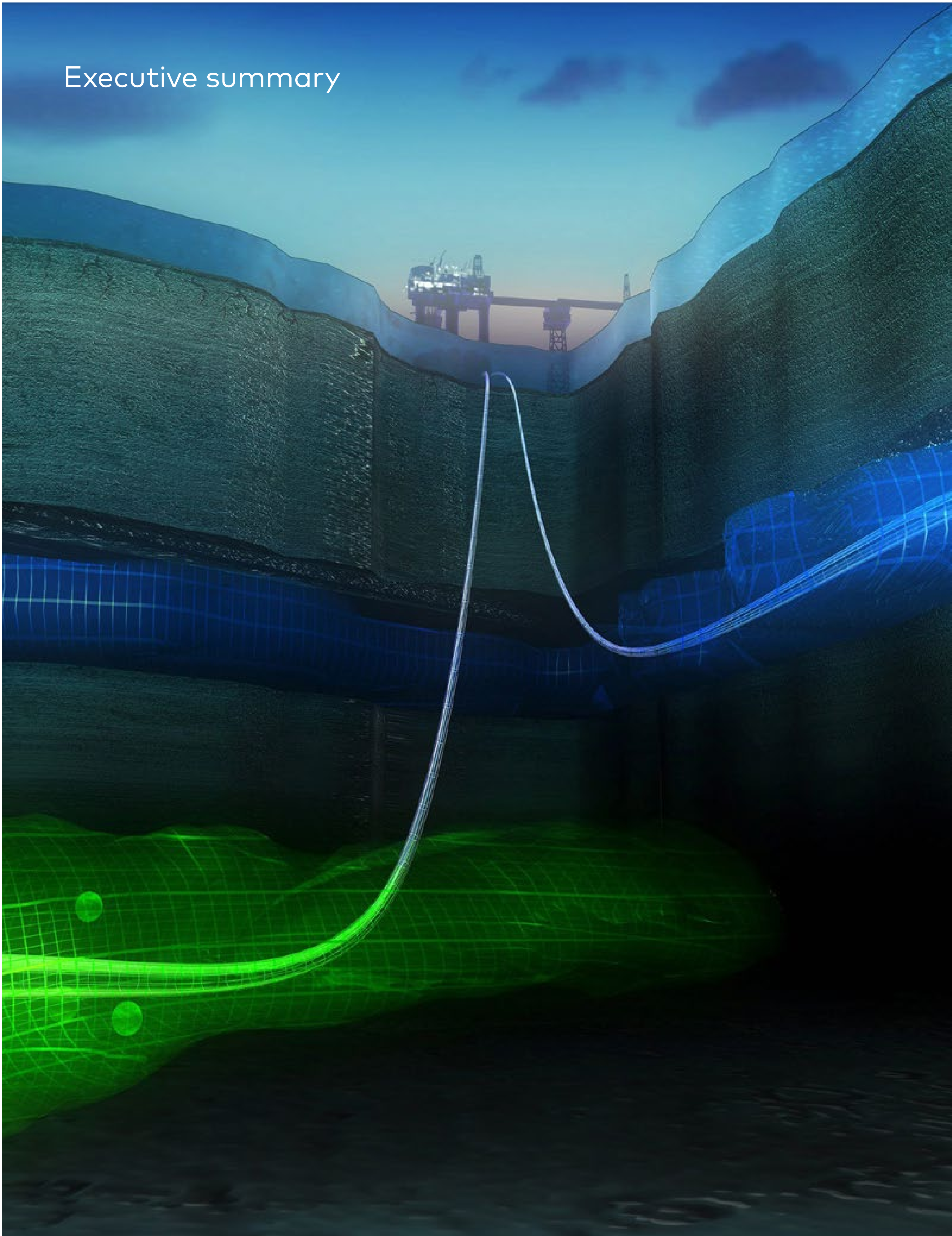

Illustration of CO_2 injection and storage on the Sleipner field in the North Sea. Illustration: Alligator film/BUG, Statoil

Executive Summary

The NORDICCS project has been a Nordic CCS platform involving major CCS stakeholders in five Nordic countries, operating under the Top-level Research Initiative (TRI). The main objective of NORDICCS has been to boost the deployment of CCS in the Nordic countries by creating a durable network of excellence integrating R&D capacities and relevant industry. The purposes were to: provide Nordic industry-driven leadership within CCS innovation and realisation, demonstrate how CCS can contribute to the Nordic portfolio of climate change mitigation options, enable the Nordic countries to join forces to become pioneers in large scale implementation of CCS, and to strengthen the competitive power of the region by combining the complementary capacities of the Nordic countries.

Project activities were organized in three categories: integrating activities, spreading excellence, and joint R&D activities. Each category included one or more of the six work packages. The Integrating Activities consisted of Assumptions and Premises (WP 1), Spreading Excellence consisted of Communication (WP 2), and the Joint R&D consisted of: Feasibility studies of Industry Cases (WP 3), CO_2 Capture (WP 4), CO_2 Transport (WP 5), and CO_2 Storage (WP 6).

Assumptions and Premises (WP 1)

The key achievement is the Nordic CCS Roadmap. This strategy document binds together and compiles the findings from the entire project into one document that shows a viable strategy for implementing CCS in the Nordic countries. The key conclusions from the Roadmap are:

- Nordic industry is largely reliant on fossil fuels, which cannot be decarbonised without CCS if climate targets are to be met.
- The Nordic region has many large biogenic emission sources, offering the opportunity for carbon-negative solutions when combined with CCS.
- With commercial-scale projects up and running worldwide, CCS technology is ready for large-scale deployment. Norway already has three CCS projects operational – two with geological storage.
- Kick-starting CCS requires the urgent development of a joint CO_2 transport and storage hub: an onshore hub and harbour fitted with unloading equipment, with a pipeline to the Utsira formation in Norway. Utsira is so vast that it could become the "CO_2 bank" of Europe, receiving CO_2 from CCS projects throughout the Nordic region as well as Northern Europe.
- Such a centralised storage site will not only accelerate deployment, but cut costs dramatically through economies of scale. Indeed, NORDICCS estimates the cost of storing the first 3 Mt of CO_2/year to be only 517 M€ in CAPEX, which results in a storage cost of 15€/tonne of CO_2. The cost of drilling an extra 3 Mt of CO_2/year-capacity well is 92.5 M€.
- In receiving such a large and continuous volume of CO_2, the hub will also kick-start CO_2-EOR projects at nearby oilfields, thus reducing CCS costs even further. However, with new oil and gas infrastructure being built now, the window of opportunity to incorporate EOR is closing.
- The most cost-effective CCS projects are centrally located in the Skagerrak cluster in developed industrial areas only a relatively short distance from Utsira.
- Transporting CO_2 by ship is the most cost-effective option in 80% of the more than 50 Nordic CCS cases analysed. Norway has already extensive experience: Yara currently ships 200,000 tonnes of CO_2/year for sale to the European food and beverage industry.
- In order for CCS to be widely deployed in time to meet climate targets, action is urgently required.

Communication (WP 2)
Key findings suggest that in order to achieve a lively societal debate about CCS, within which thorough and broadly supported decisions about CCS in the Nordic region can be made, CCS needs to be discussed by more actors and in a more concrete way. This is particularly important in those countries where a CCS debate is not that visible today. Results also show that vague policy signals are seen as problematic. Similarly, results suggest a closer dialogue between policymakers and the industry.

Improved communication is particularly important with regard to overcoming knowledge asymmetries in areas that are identified by the industry as important to increase CCS activities. In addition to this, there is a need for increased dialogue between the different countries' policymakers if the potential transnational CCS solutions investigated in NORDICCS are to become a reality.

Whereas a considerable barrier for deployment of CCS in the Nordic region presently lies within the socio-political level, communication at the local level will also be of utmost importance. Opposition towards implementation of CCS projects at the local level, particularly in Europe, has been thoroughly documented. Reflecting this, findings show that the awareness and perceptions about CCS in municipalities in the Skagerrak-region varies greatly.

Case Studies (WP 3)
Six CCS case studies (Iceland, Skagerrak, Bay of Bothnia, Sweden and Finland, Copenhagen, and Lysekil) have been undertaken in NORDICCS, covering a wide range in CO_2 volume, industry sectors, distance between sources, number of sources and distance to storage. There are many site specific parameters influencing the cost estimation results, which make it difficult to draw any general conclusions.

The capture cost is the dominating cost element. The cost of capture is mostly dependent on the CO_2 volume. The capture cost, with the assumptions used, lies in the region of 55-90 €/t CO_2. The significant span is caused due to several parameters influencing cost, such as concentration of CO_2, volume of flue gas, and also local factors.

The transport costs depend mainly on the CO_2 volumes and the transport distance, and generally lie in the region of 12-20 €/t. For most cases it was found that a ship-based transport network was the least costly solution. Transport over long distances favours ship options over pipelines. While the operational cost is higher for ships, shipping is more flexible than pipeline transport. Flexibility of transport is likely to be needed, as there are large uncertainties when it comes to the timeframe of implementation of CCS for individual CO_2 emission points.

A general storage costs is difficult to provide, since this cost is site specific. Still, an effort was made to combine storage costs and the storage sites identified give an indication of the storage cost. The cost level was suggested to be from 7 €/t for the most developed fields, to 20 €/t for the storage reservoirs with less information.

CO_2 Capture (WP 4)
Nordic point source emissions are dominated by heat and power generation, pulp and paper production, oil and gas refining, and iron and steel production. The total CO_2 emissions from facilities emitting more than 100,000 tons per year reached almost 153 Mt in 2011.

The technical feasibility of implementing CO_2 capture in the major heavy industry sectors in the Nordic countries has been evaluated. Cases were chosen to represent the sectors responsible for the largest point source CO_2 emissions in the Nordic countries. This undertaking shows that it can be feasible to apply retrofit CCS to a range of industry sectors with different process conditions.

No known CO_2 capture technology holds a clear advantage over others, but results show that it remains crucial to carefully consider the individual process and site- specific conditions on a case-to-case basis, as these strongly affect the capture technology performance and thus the choice of the most feasible technology.

The specific outcome of the case studies for cement production and oil and gas refineries show that internal differences within the processes and between the different process streams greatly affect the suitability and feasibility of CO_2 capture.

Although none of the technologies stand out as the preferred choice, post-combustion absorption of CO_2 from flue-/process gases has two major advantages; it may be applied as an end-of-pipe technology for core process operation, and it is commercially available technology, that has been used industrially for natural gas sweetening for decades. For processes with lack of excess heat, oxy-fuel combustion may be a good alternative as this technology is driven by power, not heat.

CO_2 Transport (WP 5)

When comparing cost for CO_2 transport by ship and by pipeline, ship transport has been found to be the least costly option in the Nordic region, not only for most of the individual sources but also for most of the investigated potential clusters during a ramp-up phase. The main reason for this is the combination of moderate CO_2 volumes and long transport distances.

Two of the main challenges when modelling CO_2 pipelines are to predict temperatures during the emptying of a pipe, and to assure that running fractures cannot occur. Modelling fractures requires accurate knowledge of the speed of sound, which is not available for all CO_2 mixtures. Results show that CO_2 pipelines may be more susceptible to running fractures than natural gas pipelines, so accurate modelling is necessary. To stay within the design temperature range of the pipeline, low temperatures during e.g. the emptying of a pipe should be avoided.

Simulations show that impurities like nitrogen and oxygen increase the boiling temperature, which can actually be beneficial when it comes to avoiding low temperatures. Finally, existing simulation tools for CO_2 pipelines are not yet mature, and needs further development based on better experimental data, such as for viscosity and density.

CO_2 Storage (WP 6)

An important result in NORDICCS is The Nordic CO_2 Storage Atlas that ranks potential CO_2 storage sites. The conclusion is that the Nordic region has substantial storage capacity in aquifers. The atlas identifies 20 suitable Nordic sites, with the most promising sites located in Norway. The web-based Storage Atlas comprises an extensive storage site database based on geological data from the Nordic region. The atlas can be used as basis for planning future CCS infrastructure and to support decisions on how the Nordic countries can manage their CO_2 reduction targets towards a carbon neutral Nordic region in 2050.

Interpretations of seismic surveys and exploration well logs have made it possible to map approximate outlines of reservoirs. In order to illustrate reservoir integrity and complexity, mapping of caprock (seal) formations were included, together with the fault system and exploration well locations. The GIS-database has furthermore been supplemented with information about large CO_2 emitters in the region.

A ranking procedure, based on the collected data for reservoirs and seals, has resulted in a selection of the most prospective Nordic storage sites.

Static storage capacity estimates have been compared with estimates based on dynamic simulation. One of the main conclusions of this CO_2 injection simulation was that the total storage capacity from static calculations was reduced in relation to the modelled dynamic calculations. However, even taking a reduction of static capacity estimates into account, it is obvious that the Nordic region has substantial storage capacity in saline aquifers.

In Iceland an alternative method is being developed and tested as a part of the CarbFix project (www.carbfix.com) where CO_2 is dissolved into water during injection into basaltic rock formations. Once dissolved in water, the CO_2 is no longer buoyant and does not migrate back to the surface. Basaltic rocks are reactive and contain over 25 wt% Ca, Mg and Fe-oxides. The CO_2-charged water accelerates both the metal release from the basalt and subsequent formation of solid carbonate minerals such as Calcite, Dolomite, Magnesite, Siderite, and solid solutions thereof, for long term storage of CO_2.

Communication and Dissemination of Results

Based on the communication plan, extensive efforts have been put on communication and dissemination of results from the project. Activities and results include; The website, eight newsletters, four consortium days, 11 seminars/ workshops (Section 4.4), and the Final Conference. Additionally, two one-week intensive CCS courses (CCS Summer Schools) were held for 60 PhD candidates and young researchers. A total of 112 publications have been produced during the project.

Project Partners

The following organizations have been project partners: Chalmers University of Technology, Geological Survey of Denmark and Greenland, Geological Survey of Sweden, IVL Swedish Environmental Research Institute, Norwegian University of Science and Technology, SINTEF Energy Research, SINTEF Petroleum Research, Tel-Tek, University of Oslo, University of Iceland, VTT Technical Research Centre of Finland, Gassco, Norcem, Reykjavik Energy, Statoil, Technology Centre Mongstad, and Vattenfall.

[1] Concept and Objectives

CO_2 into the warm continental shelf. Illustration: SINTEF/OXYGEN


NORGAS ALAMEDA
CO2

1.1 The NORDICCS Concept

NORDICCS has been a Nordic CCS platform involving the major CCS stakeholders in five Nordic countries, operating under the Top-level Research Initiative (TRI).

To promote a significant increase in industry-driven CCS innovation, NORDICCS has applied results from CCS research, development and demonstrations and built on the excellence within the range of Nordic industries where extensive potentials for CO_2 emission cuts have been identified. The centre has indeed represented a shaping of the Nordic CCS community and made CCS research more closely integrated with the industries, with focus on the Nordic opportunities and challenges. It has created synergies, while avoiding duplication of work, and strengthened the Nordic CCS stakeholders, reduced cross-border barriers and created a Nordic CCS network of excellence. The concept, according to which NORDICCS has been defined and managed, is illustrated in Figure 1.

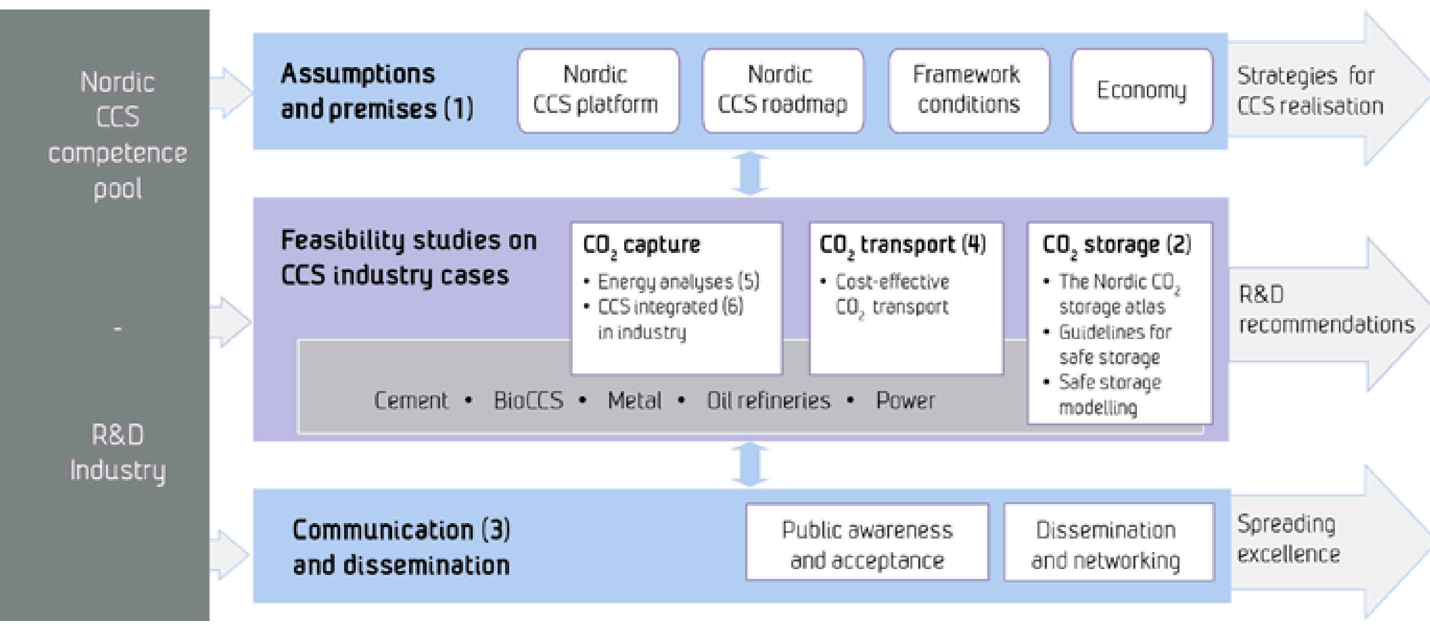

Figure 1. Illustration of the NORDICCS concept with reference to the activities defined in the call:
1. Assumptions and premises needed for realisation of CCS; 2. Geology: Nordic map of the storage potential;
3. Communication; 4. Transport-related issues of CCS, 5. Energy analysis of CCS;
6. Integration of CCS with industrial processing.

1.2 Objectives

The main objective of NORDICCS has been to boost the deployment of CCS in the Nordic countries by creating a durable network of excellence integrating R&D capacities and relevant industry with the purpose to:

- Provide Nordic industry-driven leadership within CCS innovation and realisation
- Demonstrate how CCS can contribute to the Nordic portfolio of climate change mitigation options
- Enable the Nordic countries to join forces to become pioneers in large scale implementation of CCS
- Strengthen the competitive power of the region by combining the complementary capacities of the Nordic countries

NORDICCS has involved major Nordic CCS stakeholders within academia and industry and has vastly amplified and extended the coordination and knowledge sharing occurring in the informal partner network. This has enabled the network to take an active role in paving the way for realising CCS in the Nordic countries. NORDICCS has evolved in two interlinked stages. The objectives, as spelled out in the project description, for Stage I and II are summarised below.

Objectives of Stage I: Centre building and roadmap development

- NORDICCS formalised as the Nordic CCS competence hub, as it includes:

  — The critical mass of resources and expertise required to develop and realise solutions for CCS in the Nordic Countries

  — Adequate arenas required for fostering a network attracting capacities from academia, industry and public bodies, suited for knowledge exchange and collaborative actions

  — Structures and means for coordinating ongoing and future CCS activities in the Nordic countries to exploit results, create synergies and avoid duplication of work (continuous action)

- An overall Nordic CCS roadmap developed through a joint Nordic effort, identifying required pathways and milestones for large-scale implementation of CCS.
- Established the Nordic CCS platform

Objectives of Stage II: Enabling realisation of Nordic CCS

- Identified assumptions and needed premises for CCS deployment defining a framework for CCS realisation, developed in a collaborative processes
- A program for balanced communication of current CCS knowledge to Nordic stakeholders
- Collaborative R&D projects with strategies for sharing expertise and research infrastructure. Expected results are:

  — The Nordic CCS Storage Atlas as a tool for prioritising CO_2 storage options

  — Strengthened knowledge on issues critical to CO_2 transport

  — Solutions for optimal energy use and minimum energy penalty in CCS processes based on energy analyses

- New knowledge needed to implement Nordic CCS chains resulting from

  — Case studies including various CCS integrated in Nordic industries

  — Feasibility studies including cost estimates, energy needs, market opportunities and industrial use of CO_2

NORDICCS also set out to:

- Promote programmes for education and training with extensive personnel mobility
- Promote large scale demonstration and pilots to verify identified solutions from the case studies
- Contribute to the development of national calls for funding in the Nordic countries and initiate research collaborations among the Nordic countries
- Form relevant EU calls and mobilise to enable Nordic lead in EU projects

[2] Project Approach, Management, and Cooperation

Lab at SINTEF, from left: Snorre Foss Westman, Nils A. Røkke, Ingrid Snustad, Bjørn Holst Pettersen, Ingeborg Treu Røe. Photo: NordForsk/Terje Heiestad


BIGCCS
Accurate measurements of CO2 rich mixture phase equilibria relevant for CCS transport and conditioning

2.1 Project Approach and Organization of Activities

The NORDICCS activities were organised in three categories:
The Integrating activities aimed at building the centre and defining a common basis for the partners of the centre by establishing strategic and analytic frameworks to identify assess and promote viable pathways for CCS in the Nordic countries. One activity facilitated the development of the Nordic CCS Roadmap as a joint effort among all partners during the first year of the centre and the results directed and shaped other centre activities. The activity also led to development of new knowledge on conditions required for commercialisation and deployment of CCS technology and investigated opportunities for economically viable solutions.

Spreading excellence implies communicating scientifically verified facts on CCS based on knowledge of what information is relevant and how it can be presented. It also implies disseminating existing knowledge and results from centre activities in a coordinated manner. The ability to spread excellence depends on the centre's ability to develop and operate networks for knowledge exchange among the centre partners and networks including CCS stakeholder external to the centre.

Joint R&D included collaborative research and development activities with strategies for building on the extensive pool of complementary knowledge in the consortium, and sharing expertise and research infrastructure. NORDICCS has used selected industry cases as a common basis for applying research results to define and assess potential Nordic CCS chains. The joint R&D has strengthened the excellence in selected topics, provided R&D recommendations for closing the gaps between research and realisation of CCS.

2.1.1 Integrating Activities

Assumptions and Premises (WP 1)
The Nordic CCS platform (Task 1.1) built the project as a coalition of Nordic CCS stakeholders. NORDICCS represents a model for knowledge sharing and collaboration that aimed to reduce the fragmentation of the Nordic actions to develop and realise CCS and improve coordination and interaction among the stakeholders.

The Nordic CCS Roadmap (Task 1.2). Based on a common vision for CCS deployment in the Nordic countries, a CCS roadmap envisaging a robust strategy for fulfilling the vision was developed. Main activities were to:

- Identify and involve relevant stakeholders
- Develop the Nordic CCS ambition and the timeline
- Develop CCS scenarios revealing future Nordic opportunities and barriers, exploring impact of uncertainties
- Identify the major challenges to pursue within the frames of NORDICCS

The roadmap was seen an important part of building the Nordic CCS platform. It provided a common framework and became a means for directing and coordinating other centre activities. It was reviewed and updated after two years of operation.

Economically viable solutions and market opportunities (Task 1.3). Results from the Nordic CCS Roadmap and the feasibility studies were used to define viable CCS solutions. The CCS cost model developed by the European Technology platform ZEP was applied on the industry cases to provide early cost estimations of integrated CCS solutions, taking energy use and environmental impact into account. Nordic CCS pathways were defined and analysed as part of an overall CO_2 mitigation portfolio.

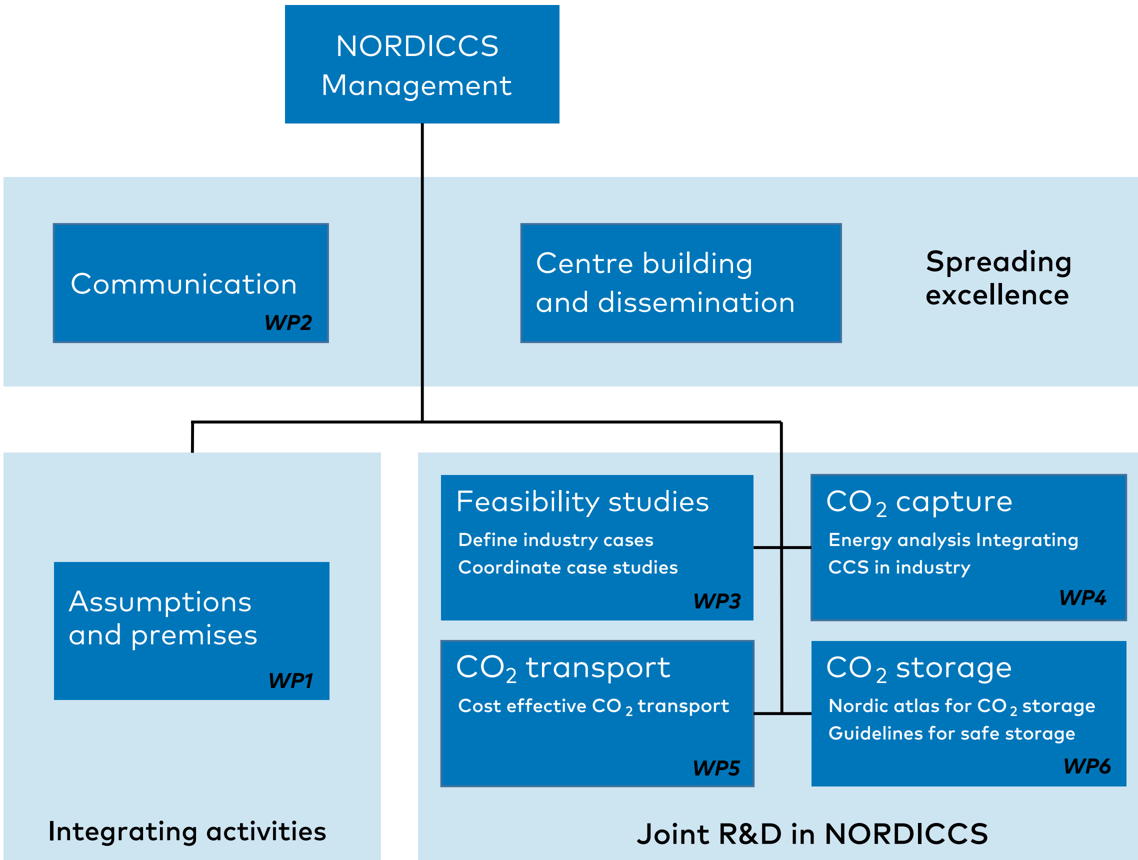

Figure 2 shows the work breakdown structure of NORDICCS.

Defining framework conditions (Task 1.4) for commercialisation of CCS technology and solutions. NORDICCS has facilitated dedicated seminars with focus on:

- Opportunities for innovation, strategies for commercialisation, value creation from CCS technology
- Legal issues with regard to CO_2 transport across borders and CO_2 storage
- Current national policies, development of a Nordic political framework for CCS
- Environmental impacts of energy production and industry with and without CCS, economic viability, storage risk

2.1.2 Spreading Excellence

Communication (WP 2)
The objective was to conduct research on CCS communication, thereby supporting balanced CCS communication in NORDICCS. To understand how to communicate CCS in a transparent and trustworthy way, it has been important to understand how communication occurs. This includes strategies to bring forward a message and knowledge on how stakeholders and the general public interpret and understand CCS. NORDICCS has built on insights from communication research and collected empirical data on present CCS communication and how people respond. Activities included:

- Preparation of an overview of communication models
- Review of public and private CCS communication strategies and analysis of CCS messages in the Nordic countries from the receivers' point of view

- Development a map on how stakeholders perceive CCS (public awareness)
- Establishment a communication program directed towards decision makers and the general public

2.1.3 Joint R&D in NORDICCS

Feasibility Studies of Industry Cases (WP 3)
The objective was to define industry cases and coordinate case studies. Main activities were:

- Definition of a set of relevant industry cases suited for case studies relevant for CO_2 capture, transport and storage
- Definition of a methodology for data acquisition, standards for process modelling and evaluation to ensure industrial relevance and quality
- Collection and synthesis of results from case studies, preparing cost estimations.
- Assembly and communication of identified knowledge gaps and recommendation to industry-driven R&D actions

CO_2 Capture (WP4)
Energy analyses (Task 4.1). The objective was to analyse and optimize energy use in CCS to reduce energy penalty. By means of generic process modelling and energy analyses, key capture technologies combined with CO_2 emitting processes were assessed to enable a high CO_2 capture performance and release a significant process integration potential by recovering waste heat. The analyses enable benchmarking of energy penalty for CO_2 capture. New knowledge on the potentials for process optimisation has been applied together with state-of-the art computation tools and models (e.g. Aspen Plus, Hysys, ProII).

Integrating CCS in industry (Task 4.2): The objective was to explore suitable CO_2 capture processes for industry cases. Suitable capture technologies for each industry were identified. By process simulations, optimal solutions for CO_2 capture were developed and an adequate degree of integration between industrial process and CO_2 capture processes was investigated. Required process modifications to enable efficient and low-cost CO_2 capture were identified. Retrofit and options were investigated. Opportunities for industrial use of CO_2 were assessed.

CO_2 Transport (WP 5)
Cost-effective CO_2 transport (Task 5.1). The objective was to conduct techno-economic assessment of options for CO_2 transport. Task 5.1 conducted feasibility analysis of transport system under different scenarios of the role of CCS considering possible integration with CCS infrastructure in Northern Europe. Cost-efficient modes for transportation were defined (pipeline/ship). Potential CCS clusters and CO_2 transport routes were defined based on industry cases and early cost estimates were developed in line with the ZEP report on CO_2 Transport Cost (December 2010).

Impact of fundamental properties of CO_2 stream (Task 5.2). The objective was to provide knowledge regarding impact of fundamental properties of CO_2 on transport and to identify issues critical to CO_2 transport in the Nordic region. Particular focus was given to impurities, as the available models of CO_2 transport in pipelines regarding safety and operation need improvements. The work was related to industry cases (WP 3) and storage (WP 6). The development of safe procedures for injection into reservoirs, first fill and depressurization of pipelines is critical and requires modelling, as well as robust, accurate and efficient numerical methods.

CO_2 Storage (WP 6)
The Nordic CO_2 Storage Atlas (Task 6.1). The objective was to review and update an existing data base and generate "The Nordic CO_2 Storage Atlas". European R&D on CO_2 storage capacity only included data from Denmark and part of Norway. The input data was extended to cover the rest of the Nordic area. A clear distinction between geological formations forming regional aquifers with potential for CO_2 storage and individual geological structures and traps are not well established in the European projects. Geological formations with sealing properties have not been previously mapped. Main activities were:

- Creation of a geographic information system (GIS) database as basis for the Nordic CO_2 Storage Atlas
- Addition of missing storage resources (hydrocarbon reservoirs, aquifers and sealing formations)
- Development of a clear distinction between regional aquifers with potential for larger scale CO_2 storage and local geological structures and traps

- Ranking of geological structures based on storage guidelines
- Making the Nordic CO_2 Storage Atlas publicly accessible as a Web-based GIS

Guidelines for Safe Storage in the Nordic area (Task 6.2). The objective was to define criteria, methods, and timeframe for safe storage of CO_2 in the underground in the Nordic region. A framework was specified for safe storage in the Nordic areas, with respect to a timeframe, storage capacity and depth, and distance from source. A catalogue was set up with input data needed to characterize a storage site as safe. A unified Nordic understanding of data and modelling tools needed to quantify capacities and uncertainties in storage was developed. Deliverables:

- Optimised exploration program to cover knowledge gaps in storage potential
- Nordic Storage Guidelines
- Evaluation of the role of carbon mineralization in basalt in the Nordic region

Safe Storage Modelling (Task 6.3). The objective was to illustrate and narrow the uncertainty in storage capacity assessment. To investigate the filling capacity for selected storage site cases, a methodology for improved storage capacity estimation was described by combining existing tools. Modelling of test scenarios helped to understand complex processes that influence the safety aspect and the storage capacity, e.g. pressure build-up, sealing properties, dissolution of CO_2, diffusion induced convection and capillary trapping. Main activities were:

- Screening of the Nordic CO_2 Storage Atlas with respect to the storage criteria
- Selection of Nordic key case studies where dynamic modelling were used to test safe storage
- Improved capacity estimations based on site specific modelling
- Quantification of uncertainty in capacity estimates, and sealing properties

2.2 Management Structure

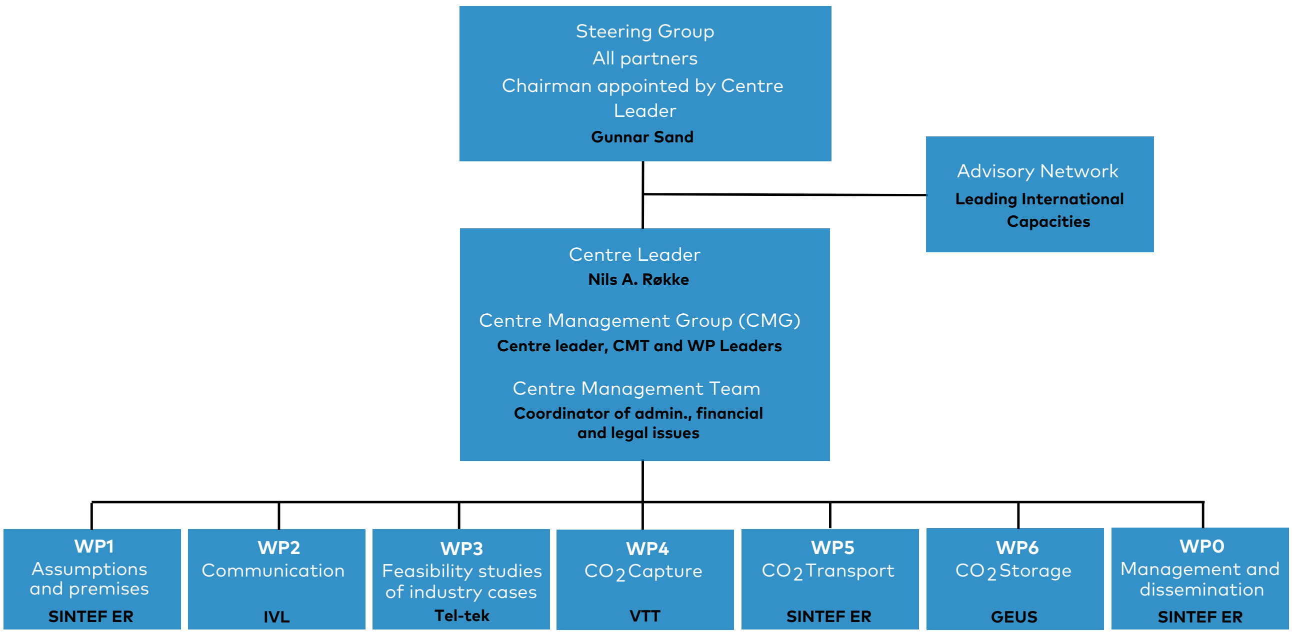

Figure 3 Management structure of NORDICCS

NORDICCS is a virtual interdisciplinary competence centre. The activities are conducted in dedicated topical workgroups, in workshops and seminars as part of the roadmap process and other collective undertakings and in virtual arenas organised by the centre. A management framework was set up to ensure autonomy, information exchange, governance and clearly defined responsibilities.

Centre Management

The management structure is shown in Figure 3. SINTEF Executive Vice President Sustainability, Dr. Nils A. Røkke was the responsible Centre Leader. The Centre Leader managed the project and has operative responsibility for the organisational and technical efficiency of the project.

NORDICCS was organised in six work packages (WP) and for each WP a responsible partner was appointed as WP Leader. The WP leaders were responsible for preparing plans and executing the work within the Centre contracts and in accordance with budgets and deliverables defined in approved plans. All WP leaders were members of the Centre Management Group (CMG) administrated by the Centre Leader, and a balance between country representations in the group was sought. The Centre Leader operated mainly with the WP leaders and reported to the Steering Group.

The Centre Leader interfaced with TRI on scientific, technical and administrative matters related to the project. He was supported by the Centre Management Team (CMT) in charge of the administrative, financial and legal tasks.

All parties to the Consortium Agreement were full and equal members of the Steering Group (SG), reflecting the balance between of the consortium. Voting in the SG was by simple majority. The SG were to meet at least once per year. SG members or the Centre Leader could always call for extra meetings. As contract partner with TRI, SINTEF Energy Research nominated the chairman, who was Mr. Gunnar Sand of SINTEF Energy Research. The SG was responsible for the quality and progress of the work in the WPs towards TRI and the financial contributors. The SG decided on the budget, the contents, the distribution of the partner financing of the WPs, and approved the annual implementation plans.

2.3 Cooperation between Partners

In NORDICCS, effort were on establishing and operating adequate networks. All networks were formed based on identified needs of interaction. Participants and work processes varied depending on the purpose.

The Integrated activities were important for building the centre, forming the NORDICCS strategies and enabling the overall assessments to be conducted. Most important was the formalisation of NORDICCS as the Nordic CCS platform. Annual conventions were held where all partners shared results and discussed topics of common interest. The NORDICCS Roadmap was developed as a joint effort during the first year. In addition to providing the strategic framework for the centre the roadmap development was important for establishing NORDICCS as a Nordic CCS community.

Dedicated seminars inspired by think tank models were organised to collect knowledge and provide recommendations regarding framework conditions. For topics outside the core competence of the partners, specialists were subcontracted to facilitate the seminars and to extract the findings. Seminars were open and the results were made available through NORDICCS external channels of communication.

Joint R&D activities focused on specific scientific topics and were organised in work groups. WPs on CO_2 capture, CO_2 transport and CO_2 storage included partners across the Nordic countries and were typically topical networks for interactive work. Information exchange between the WPs was significant and the activity 'Feasibility study' was important for WP coordination. The topical networks drew on the members of each centre partner's professional networks.

2.4 Project Partners

The following organizations have been partners in the NORDICCS project:

R&D Partners

1. Chalmers University of Technology, Sweden
2. Geological Survey of Denmark and Greenland, Denmark
3. Geological Survey of Sweden, Sweden
4. IVL Swedish Environmental Research Institute, Sweden
5. Norwegian University of Science and Technology, Norway
6. SINTEF Energy Research, Norway
7. SINTEF Petroleum Research, Norway
8. Tel-Tek, Norway
9. University of Oslo, Norway
10. University of Iceland, Iceland
11. VTT Technical Research Centre of Finland, Finland

Industry Partners

12. Gassco, Norway
13. Norcem, Norway
14. Reykjavik Energy, Iceland
15. Statoil, Norway
16. Technology Centre Mongstad, Norway [a]
17. Vattenfall, Sweden [b]

(a) TCM became partner at Steering Group meeting No. 3, 2012-09-06 (Amendment No 2)

(b) Vattenfall became partner at Steering Group meeting No. 4, 2012-12-14 (Amendment No. 3)

[3.0] Project Achievements

The CarbFix project. Testing facility for CSS outside Reykjavik. Photo: NordForsk/Terje Heiestad

3.1 Assumptions and Premises (WP 1)

3.1.1 Highlights

The Nordic CCS Roadmap
The key achievement from WP 1 is the Nordic CCS Roadmap. This strategy document binds together and compiles the findings from all the NORDICCS WPs into one document that shows a viable strategy for implementing CCS in the Nordic countries. This is also the main deliverable D7, to Nordic Innovation from WP 1.

The Nordic CCS Roadmap was first issued in November 2013 (Publication no. 4) with an update issued in November 2015 for presentation at the COP21 meeting in Paris (Publication no. 12).

One of the main findings from NORDICCS is that ship transport provides the most cost effective transport of CO_2 for 80 % of the CO_2 capture cases in the Nordic region (Publication no. 44). Cost estimates show that one way of gaining significant benefits from economy of scale is therefore to build a joint storage site in the North Sea to which CO_2 can be easily transported by ship.

An onshore hub and harbour is proposed fitted with unloading equipment, with a pipeline to the offshore Utsira formation in Norway, which has already been storing CO_2 from Sleipner for nearly 20 years. It is further proposed that CO_2 from various sources in all the Nordic countries can be shipped to this hub, as illustrated in Figure5.

A detailed cost analysis was performed for numerous potential CO_2 capture projects. It was found that the most cost-effective CO_2 capture projects are centrally located in developed industrial areas in the Skagerrak cluster, only a relatively short distance away from the Utsira formation and CO_2 hub.

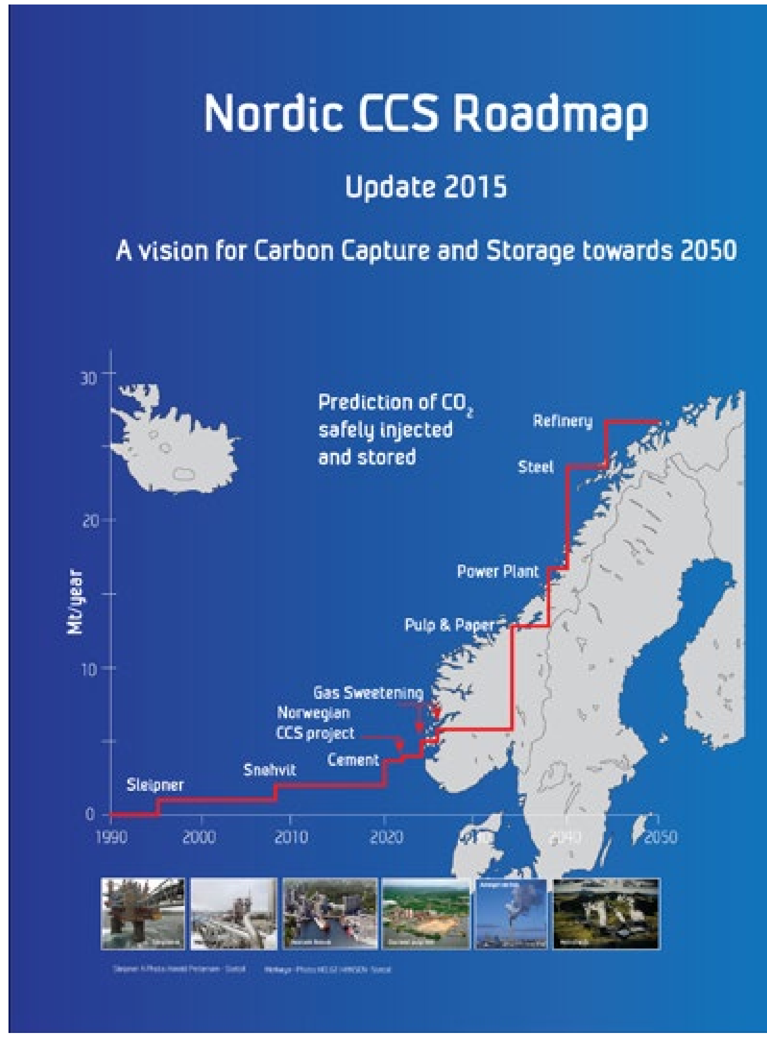

Figure 4. The Nordic CCS Roadmap

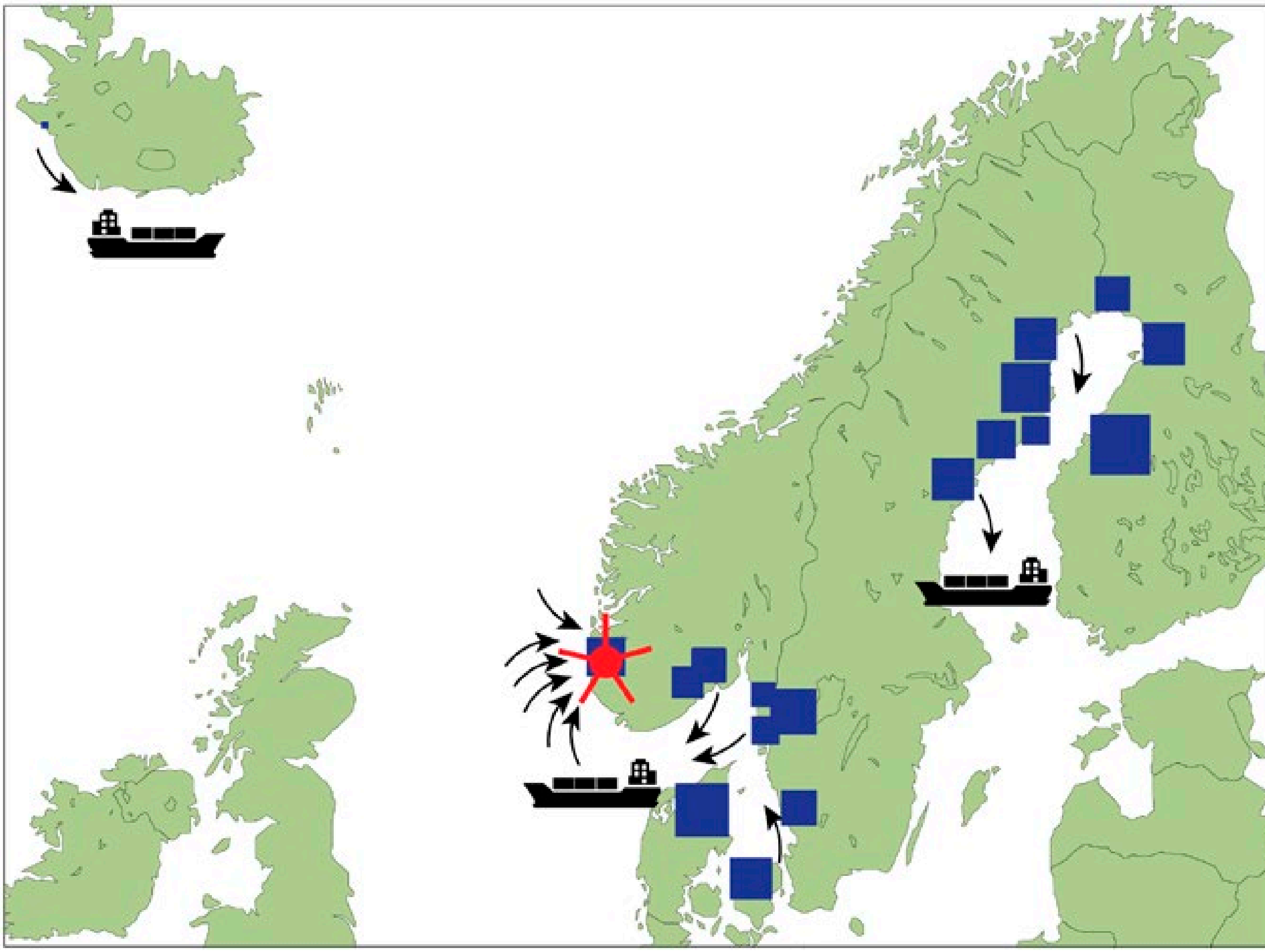

Figure 5. Ship transport of CO_2 from sources in the Nordic Region to joint Nordic storage at Utsira.

The Portland cement plant in Ålborg, Denmark and the Norcem cement plant in Brevik, Norway, were the lowest-cost CCS projects evaluated. The Norcem cement plant emits 0.8 Mt of CO_2 per year and we estimated that the most economically viable CO_2 capture project would capture 0.4 Mt tonnes of CO_2/year. The capture process would then use large amounts of waste heat recovered from the cement production in the CCS process to make CCS more economically viable. However, in this report, the cost estimate is based on publicly available information on the process, and assumes a CO_2 capture rate of 0.8 Mt/year. The cost of capture, considering the location factor[(c)], is 59 €/t of CO_2.

The Norwegian Government (via Gassnova) awarded Norcem founding for a feasibility study for the commercialisation of CCS at their cement plant in Brevik in October 2015.

Portland Aalborg has a larger cement plant emitting 1.15 Mt of CO_2/year and the capture cost was estimated at 57 €/tonne. In both cases, transport and storage costs are based on shipping the CO_2 to Utsira.

(c) *The location factor* reflects variations in costs due to different location, i.e. labor, shipment, direct expenses, etc

The roadmap "key conclusions" summarizes the NORDICCS project's main findings and recommendations to Nordic politicians (grey box below).

Key conclusions – Nordic CCS Roadmap

- Nordic industry is largely reliant on fossil fuels, which cannot be decarbonised without CO_2 Capture and Storage (CCS) if climate targets are to be met.
- The Nordic region has many large biogenic emission sources, offering the opportunity to actually achieve carbon-negative solutions when combined with CCS (Bio-CCS).
- With commercial-scale projects up and running worldwide, CCS technology is now ready for large-scale deployment. Norway has already three CCS projects operational – two with geological storage, and one with sales of CO_2 – with more in the planning.
- Kick-starting CCS requires development of a joint CO_2 transport and storage hub: an onshore hub and harbour fitted with unloading equipment, with a pipeline to the Utsira formation in Norway (which has already been storing CO_2 from Sleipner for nearly 20 years). Utsira is so vast that it could become the "CO_2 bank" of Europe, receiving CO_2 from CCS projects throughout the entire Nordic Region as well as Northern Europe.
- Such a centralised storage site will not only accelerate deployment, but also cut costs dramatically through economies of scale. Indeed, NORDICCS estimates the cost of storing the first 3 Mt/year to be only 517 M€ in CAPEX, which results in a storage cost of 15€/tonne of CO_2. The cost of drilling an extra 3 Mt of CO_2/year-capacity well is 92.5 M€. Three additional wells can be added for a total of 12 Mt of CO_2 stored.
- In receiving such a large and continuous source of CO_2, the hub will also kick-start CO_2-EOR projects at nearby oilfields, thus reducing the costs of CCS even further. However, with new oil and gas infrastructure being built now, the window of opportunity to incorporate EOR is closing.
- The most cost-effective CCS projects are centrally located in the Skagerrak cluster in developed industrial areas, which are only a relatively short distance from Utsira.
- Transporting CO_2 by ship is the most cost-effective option in 80% of the 50+ Nordic CCS cases analysed. Norway has already extensive experience: Yara currently ships 200,000 tonnes of CO_2/year for sale to the European food and beverage industry.
- In order for CCS to be widely deployed in time to meet climate targets, action is therefore urgently required. This includes:

  — Creating public investment in the first transport and storage hub in the North Sea – shared by all the Nordic governments and where all the Nordic countries have rights to store CO_2

  — Prioritizing products with a low-carbon footprint in governmental project purchasing, e.g. green cement, steel and aluminium

  — Using the CO_2 hub to kick-start CO_2-EOR in the North Sea and reducing the costs of CCS even further – recognising that the window of opportunity is narrowing

  — Establishing CCS support measures until the EU Emission's Trading System (EU ETS) can deliver a meaningful carbon price in the longer term. For example, early CCS projects require capital grants since a 'first-of-a-kind' unit will always be more expensive than an 'nth-of-a-kind' unit.

  — Strengthening the EU ETS as the long-term driver for CCS and rewarding the capture and storage of biogenic CO_2 to the same extent as for fossil CCS

  — Establishing a Measurement Reporting Guideline which allows CO_2 transport by ship under the EU ETS

  — Undertaking a feasibility study of a joint transport and storage hub for a complete CCS value chain by 2017 in order to meet the Government's goal of a full-scale project in Norway by 2020.

Panel discussion at NORDICCS seminar. Photo: Mette Kjelstad, SINTEF

The other highlight from WP 1 is the Innovation Seminar series arranged as an annual series of seminars throughout the project in order to collect knowledge and provide recommendations regarding framework conditions as input to the Nordic CCS Roadmap. The seminars were inspired by think-tank models with multiple expert presenters and round-table discussions. The seminars were a successful example of the goal for WP 1: to help put CCS on the agenda of Nordic decision makers and to provide information on CCS strategies to help support political decisions as well as informing the public of CCS. Action from politicians is essential for implementation of CCS. Changes are needed to the European carbon market as it is not effective enough to kick-start CO_2 capture, and additional measures may also be needed. Governmental support is needed for development of CCS infrastructure. These are all necessary instruments in order to promote widespread implementation of CCS. Key results from each of the Innovation Seminars are given below.

2012 Seminar: Barriers and Opportunities for CCS Innovation and Implementation

The seminar included top politician Nikolai Astrup (Høyre, Norway) as well as representatives from industry and NGOs. The outcome of the seminar is summarized in Deliverable D 1.4.1201 "Opportunities for Implementing Nordic CCS". Here, barriers such as financing, public acceptance, risks and changes to framework conditions were discussed. Some of the contents became a part of the roadmap.

2013 Seminar: Workshop on Nordic CCS Roadmap – Framework Conditions

The outcome of this seminar was a list of important framework conditions for implementing CCS in the Nordic countries, documented in D.1.4.1301. This report evaluates ETS, taxes, and identifies a framework condition particularly important for the Nordic countries, i.e. the need to establish Measurement Reporting Guidelines (MRG) for ship transport of CO_2 enabling ship transport across country borders. SINTEF and VTT collaborated on a MRG project following this seminar.

Lamberto Eldering, Statoil.
Photo: SINTEF

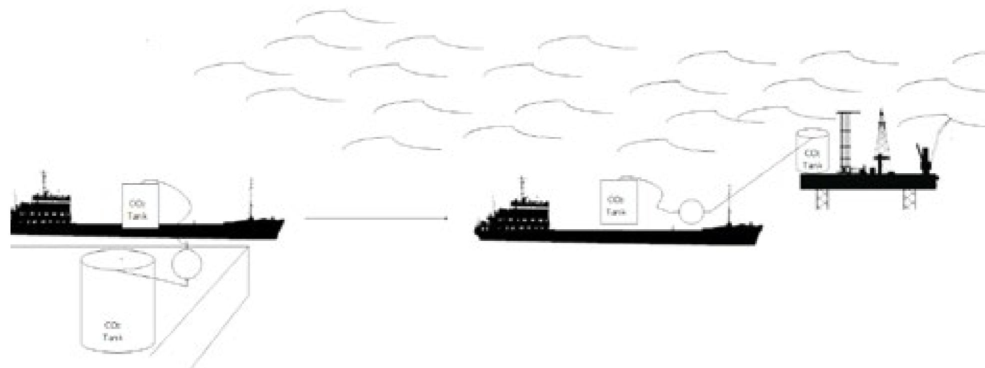

Figure 6. MRR for Ship Transport of CO_2, from presentation by Marit Mazzetti, SINTEF Energy Reseach

2014 Seminar: Workshop:
Legal Issues in CO_2 Transport

Key conclusions from the Legal Issues workshop are summarized in D.1.4.1401:

- All risk elements in the value chain need to be quantifiable, manageable, predictable and in balance with expected revenue
  - Cap on liabilities
  - Flexible support mechanism
  - Sufficient rate-on-return
- CCS policies need to be formulated such that industry can expect that there will be a scale-up of projects soon after the first projects are realized (long-term vision)
- Unnecessary barriers should be removed especially for first-of-a-kind projects (first mover advantage)
- Complexity of CCS value chains requires high involvement of government. It is too big and complex to be taken on by industry alone – public-private partnership is needed.
- Norwegian law:
  - No law or regulation regarding transfer of long-term liability
  - Norway is obligated to implement CCS Directive
  - Two draft regulations are in the works
- Conditions for transfer may be stipulated in the license
- Petroleum Law: There is currently no Measurement Requirement Regulation (MRR) for transport of CO_2 by ship. There is therefore a need to amend Commission Decision 2012/601/EC of 21 June 2012 to include a MRR for transport of CO_2 by ship for the purpose of geological storage/EOR.

2015 Seminar: Bio-CCS Technologies & Sustainability

The last of the four seminars focused on bio-CCS. The seminar was held during the TCCS-8 conference in Trondheim in June 2015 and had about 30 attendees and very engaging discussions about the sustainability issues related to bio-CCS. Excellent presentations conducted by Dr. Florian Kraxner of Switzerland, Dr. Sabine Fuss of Germany and Mr. Jonas Helseth from Bellona gave insight into bio-CCS outside the Nordic region and on a global basis. The seminar highlighted that bio-CCS is necessary to meet climate goals in order to remove CO_2 from the atmosphere. However, at the same time its land-use must be integrated at a global basis in order to ensure sustainability and avoid hindering food production. Biomass co-firing was indicated by several of the speakers as a means of kick-starting bio-CCS. A summary of the workshop is given in D 1.4.1501.

3.1.2 Description of Activities

WP 1 was divided into four Tasks:

The Nordic CCS Platform (Task 1.1)

This task organized workshops and project networking events, and assisted in annual project meetings and participated in other WP workshops.

The Nordic CCS Roadmap (Task 1.2)

The final NORDICCS Roadmap was a result of four years of work. Many public seminars and NORDICCS workshops were held with topics relevant to creating the strategy document where all NORDICCS researchers participated. The joint knowledge in the consortium was then distilled into a strategy for the Roadmap. Detailed cost analysis was performed for the most viable NORDICCS scenarios, along with work on policy and framework conditions in collaboration with external groups such as Bellona and ZERO among others. A natural gas sweetening CCS project was found to be particularly economically viable and was cost analyzed in detail in a separate project for which WP 1 was awarded extra funding for performing in 2013 (Publication no. 5).

Economically Viable Solutions for Nordic CCS (Task 1.3)

This task performed the techno-economic analysis of capture and joint storage project for the Nordic CCS Roadmap and arranged a workshop at Chalmers in 2014, reported on in the dissemination section.

Defining Framework Conditions (Task 1.4)

Four public seminars were organized, one each year in 2012-2015, with the intent to collect knowledge and provide recommendations regarding framework conditions for input to the Nordic CCS Roadmap as described in the previous section.

Spin-off projects

Three spin-off projects were developed from WP 1:

- Natural Gas Sweetening Techno-economic analysis (200 kNOK, 2013)
- Nordic CCS Summer School 2013 (2 MNOK)
- Nordic CCS Summer School 2015 (2 MNOK)

Dissemination

WP 1 produced six conference presentations and three publications in refereed journals.

News/Media Publications & Blogs

Two news articles in Norwegian news publications were produced in Teknisk Ukeblad:
www.tu.no/forskning/2013/11/17/co2-rensing-koster-minst-pa-sokkelen

and Adresseavisen:
www.adressa.no/nyheter/okonomi/article8645697.ece

A chronicle, written by Marit Mazzetti and Nils Eldrup, is accepted for publication, in Dagens Næringsliv (www.dn.no) during January or February 2016. As soon as this is issued the same chronicle will be attempted published in a Danish, Swedish and Finnish newspaper as well.

3.1.3 Industry Benefits

NORDICCS WP 1 has performed strategic research on CCS implementation that the industry partners do not perform themselves. Oil and gas companies do not generally carry out strategic projects on this scale. This was specifically mentioned by partner Statoil during their summary of the project at the final NORDICCS meeting. They also commented on the strategy work being important with respect to framework conditions.

In the case of CCS, Nordic collaboration has been shown to be particularly beneficial as there are mutual benefits in collaboration between Sweden and Finland, who have large industries with large point sources of CO_2, with Norway and Denmark, who have smaller CO_2 sources but vast storage capacities offshore. Such collaboration can allow a joint storage, which in turn will promote economy of scale and therefore may be able to help kick-start CCS in the Nordic countries. Hence, NORDICCS has contributed in helping the industry partners communicate a strategy for CCS.

Industry also benefits from NORDICCS researchers communicating the results out via media, newspapers and journal publications as well as directly communicating to politicians, as this may help CCS become implemented in the Nordic countries.

3.2 Communication (WP 2)

Preem Refineries, Sweden. Photo: Preemraff

3.2 Communication (WP 2)

3.2.1 Highlights

The need for increased debate and policy clarifications
Policymakers represent an important stakeholder group to direct attention to when it comes to understanding overall national societal debates. Without political discussions and policies being developed for CCS, deployment of CCS will most likely not be a reality in the Nordic region.

NORDICCS findings suggest that in order to achieve a lively societal debate about CCS, within which thorough and broadly supported decisions about CCS in the Nordic region can be made, CCS needs to be discussed by more actors and in a more concrete way. This is particularly important in those countries where a CCS debate is not that visible today (all Nordic countries except Norway). In several Nordic countries, CCS has been acknowledged as having a role to play in long-term energy and emission scenarios. Still, the question of whether to take steps towards realization of CCS or go for other emissions-curbing options instead, is in many cases left open. This is unfortunate, given the time it takes to get a large scale CCS project in place versus the urgent need to cut emissions. National policymakers need to send clear signals concerning what future development they envision.

NORDICCS results also show that vague policy signals are seen as problematic. Swedish industrial actors, for example, have requested clarity about Swedish CCS policies; whether CCS in fact is a priority and what measures that will be taken. Similarly, our results have also pointed to quests for closer dialogue between policymakers and the industry. Norwegian and Swedish industry representatives generally perceive communication with policymakers to be poor. Improved communication is particularly important with regard to overcoming knowledge asymmetries in areas that are identified by the industry to be important to increase CCS activities. In Sweden, knowledge about policy was regarded in the survey as the most desired knowledge area, and the second most important in Norway next to costs.

Moreover, the industry in Sweden and Norway perceived policymakers to have extensive knowledge about this topic. However, as mentioned, Norwegian and Swedish industry representatives generally perceive communication with policymakers to be poor and increased communication with policymakers about this knowledge area is seen as essential to move forward with CCS.

In addition to this, we found that there is a need for increased dialogue between the different countries' policymakers if the potential transnational CCS solutions investigated in NORDICCS are to become a reality in the Nordic region. Today, dialogue between policymakers in Norway, Sweden and Denmark about transnational CCS solutions is absent and there are no concrete policies for joint CCS activities. Our findings show, however, that there are some aspects of national policies that may facilitate for a realization of transnational solutions, which could form a starting point for political discussions between policymakers.

The importance of creating awareness about CCS at the local level
Whereas a considerable barrier for deployment of CCS in the Nordic region presently lies within the socio-political level, communication at the local level will also be of utmost importance. Opposition towards implementation of CCS projects at the local level, particularly in Europe, has been thoroughly documented. For the Nordic situation, the status of actual CCS implementation and experiences with the technology varies greatly between the different countries. Norway currently has two large scale projects at Sleipner and Snøhvit, whereas no large scale CCS project has been realized in the other countries. As there are few projects that have been realized or planned in the Nordic region, there are few experiences and research to draw lessons from in this region.

Reflecting this, our findings show that the awareness and perceptions about CCS in municipalities in the Skagerrak-region varies greatly. Porsgrunn in Norway (location of Yara Norge AS and Norcem AS, see Figure 7) is the only municipality that shows high awareness about the technology. CCS is in the Swedish municipalities seen as an interesting option to reduce CO_2 emissions; however, the awareness about CCS among municipalities was low[d].

In Norway, on the other hand, Porsgrunn municipality displayed very positive attitudes towards existing and potential CCS activities, which stands in contrast to the many conflicts experienced in Europe. Porsgrunn has long industrial traditions and a large share of the inhabitants work in the industry and are used to industrial activities and related environmental challenges. Moreover, the local community has experiences with CCS activities, as Yara has extensive experience with capturing CO_2 from their ammonia production and transporting it by ship to Europe for use in beverages. Norcem has tested three different CO_2 capture technologies at their cement plant, and plan to go on with testing of two of them, while the third technology is a candidate for full-scale CO_2 capture. The municipality has not experienced any major public protests from these activities. On the contrary, Porsgrunn municipality sees CCS technology as a way of promoting and profiling the local community and the region as an environmental and technological leader, preventing depopulation and maintaining and developing new industrial activities. Furthermore, research and development of CO_2 reuse for industrial purposes is seen as a particularly interesting option to create new local business development.

In order to raise awareness and increase knowledge locally, one possibility is to set up a dialogue platform in areas which could potentially become sites for future exploitation of CCS, such as the Skagerrak region, Figure 7. A dialogue platform would be a way for municipalities in the same region to build knowledge, share their experiences, debate common interests and overcome knowledge asymmetries. Our findings also suggest that gaining knowledge about local communities' perceptions about possible CCS projects is of importance for policymakers to create robust and socially anchored national policies. Hence, it can be beneficial to view the national and local level as potentially interdependent and to communicate the outcome of such discussions to provide input to national policymakers.

Importance of engaging the public and taking local concerns into account

Closer to actual project implementation, we have identified two main communication approaches that may be used when communicating with the public. The transmission approach is similar to a one-way information transfer, whereas the participatory approach, on the other hand, can be described as a multi-directional dialogue. The two approaches have different characteristics with regard to communication objective, communication direction, view of the sender and view of the message.

The two approaches also differ with regard to strengths and weaknesesses. The transmission approach is suitable if the sender wants to retain control over the message, create a clear message, limit its dependence on public engagement and save costs and money on communication activities. On the down-side, it may miss out on important insights regarding local, social or contextual factors, limit learning and raise risks of public mistrust. The participatory approach, on the other hand, has the possibility to take local, social or contextual factors into account, foster trust and allows for learning. Weaknesses may include giving up control over the message, raise risks of creating a multifaceted message that may create confusion and concern, being dependent of possibly costly and time-consuming public engagement processes, and risking engaging only certain groups in society. Hence, the strengths of the transmission approach to a great extent match the weaknesses of the participatory approach and vice versa.

(d) As no one in Aalborg municipality currently works with CCS, it is uncertain how the municipality would look at a new CCS project.

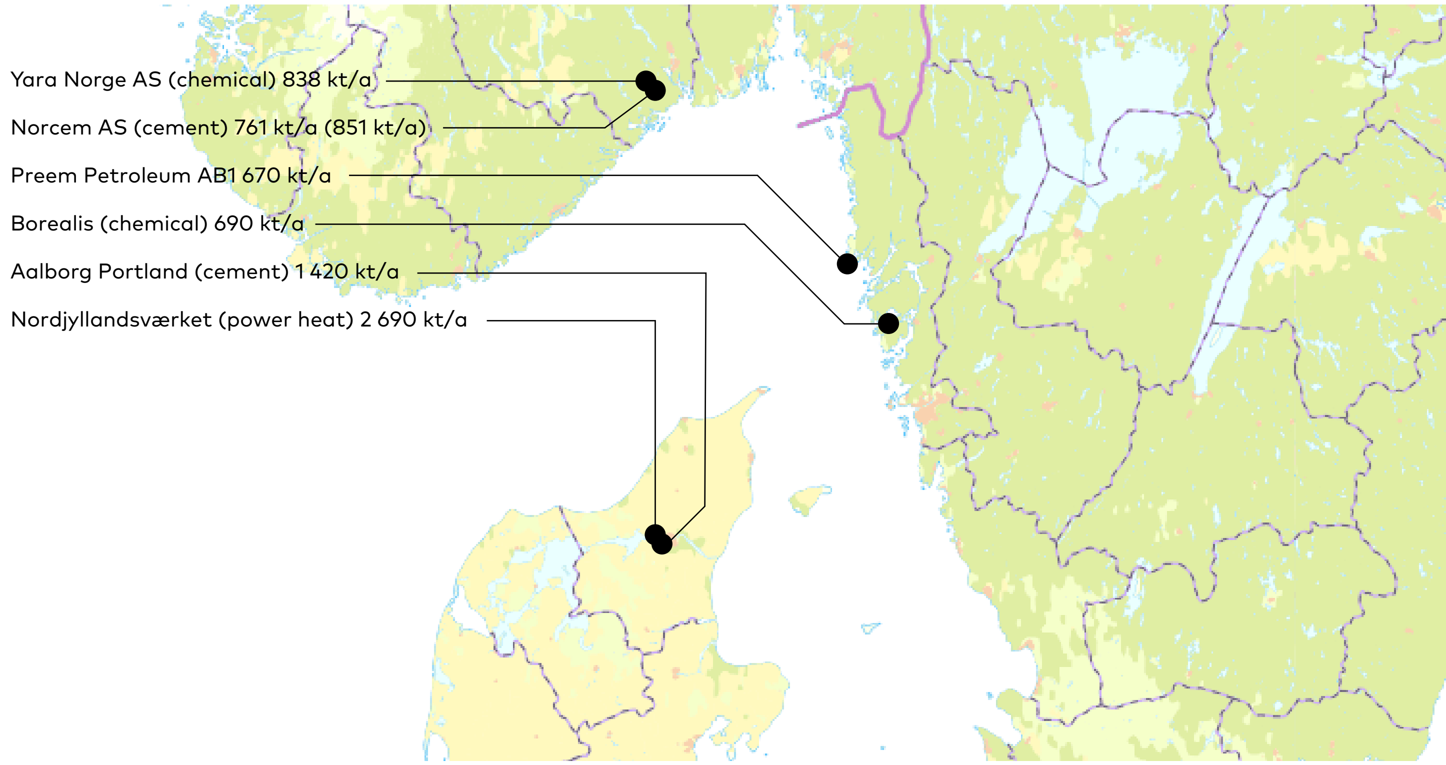

Figure 7. A map over the Skagerrak cluster with its emission sources. CO_2 transportation using both ship and pipeline and storage in the Gassum formation and Utsira formation has been assessed. Source: Skagestad et al. 2015

Irrespective of choice of the communication approach, it will be essential to take local factors into account in the communication effort. We have pointed to literature that suggests that it is important that communication is designed to provide a fair process through which certain decisions are reached and aim for a fair outcome with acceptable distribution of costs and benefits. As described above regarding the Skagerrak-case, our findings in NORDICCS suggest that it is important to pay attention to and to gain knowledge about the history, identity and future plans of the local community. These were significant factors for the positive attitudes towards existing CCS activities in Porsgrunn municipality in Norway.

Our findings also suggest that the possibility to store CO_2 offshore in the Nordic region could contribute to a low level of conflict. The possibilities for offshore storage of CO_2 has in the literature been suggested as a factor strongly contributing to a low level of controversy, and the Nordic region has on this background been suggested as a region well suited for CCS. However, there actually exist few in-depth studies of perceptions towards offshore CO_2 storage to underpin this. Nevertheless, storage of CO_2 has not been a source of conflict in Porsgrunn and is predicted to be relatively unproblematic for future projects as the storage would take place offshore or in CO_2 reuse. The offshore storage was also highlighted as a clear advantage for the Nordic region by national authorities. Nevertheless, it will be vital to engage in a close dialogue with the local public, including maritime stakeholders, to be able to identify where CCS projects are most suited and to ensure a fair and transparent process.

3.2.2 Description of Activities

Background

The insight that attitudes and opinions about CCS is of utmost importance for its success or failure have hardly bypassed anyone working professionally on the topic. A growing collection of social scientific studies has among other things informed us that these social phenomena are highly dependent on the communication of CCS, which in turn is colored by its context (cf. Ashworth et al. 2015).

Despite the longstanding pioneering role of Norway and widespread curiosity about CCS from the neighboring countries, information has been lacking about CCS communication among the public and various stakeholders in the Nordic region. There are also valuable lessons to be learnt by relating insights from previous CCS communication research to the Nordic context. Against this background, NORDICCS devoted a work package to examine communication issues from several perspectives, with a particular focus on the Nordic region.

Research approach

In this work package we have conducted research on several topics pertaining to CCS communication in the Nordic region. Firstly, we have conducted a review of different models of communication where we have explained and discussed what assumptions suggested by the respective theories underpin limited and extensive public engagement. Secondly, we have looked at how Nordic policymakers have communicated about CCS in national policies and in press releases and news. Thirdly, we have developed a methodology for stakeholder mapping, where Nordic stakeholders and their knowledge or lack thereof, as well as desired knowledge have been described. Fourthly, we have explored the local dimension of CCS, theoretically and empirically, to understand the preconditions for CCS project development in local communities in the Nordic region.

Figure 8 depicts the ways in which our research has been designed to illuminate different stakeholder groups and geographical scopes. By demarcating our research this way, the analysis of CCS communication becomes more manageable. Altogether, the sub-studies of this work package provide a multifaceted Nordic perspective on CCS communication.

The different work tasks builds on a literature review of scientific articles and other reports, qualitative analysis of policy documents, surveys and interviews. The methodological approaches are described more in depth in each report (see references).

3.2.3 Industry Benefits

Our findings point to several factors that are important for the industry to take into account when communicating about CCS. First, our findings describe various challenges and opportunities at the political level that should inform and be an integral part of communication efforts. Moreover, our research provides a methodology which can be used as a tool to identify priorities for communication efforts to increase action on CCS through overcoming knowledge asymmetries. The methodology also enables identifying other factors that are important to increase CCS activities.

Furthermore, our research is of relevance for industries when communicating with their respective local communities. Our findings have pointed to important existing experiences with local communities that should inform communication efforts, as well as pros and cons with different communication approaches. This gives valuable knowlege that is important for designing communication plans in a thorough way. In addition to our work, several internationally derived CCS communication guidelines and toolkits are available for those who seek hands-on advice, such as the guidelines for community engagement regarding CCS launched by the World Resources Institute (2011) and CSIRO's (2010) communication and engagement toolkit for CCS projects.

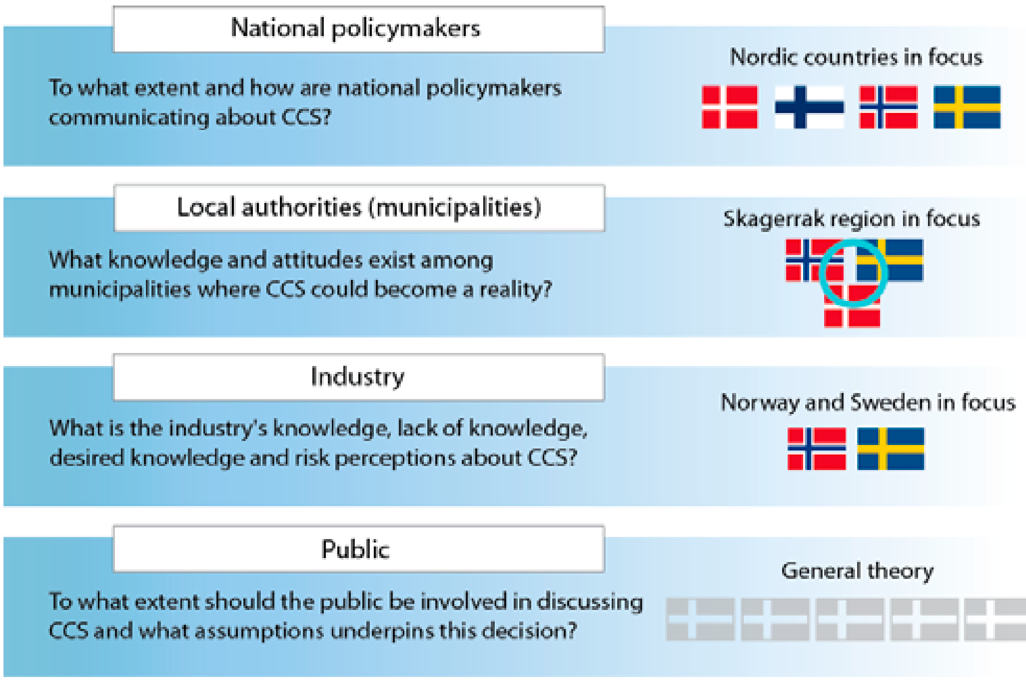

Figure 8. Examined stakeholder groups and examples of research questions, related to geographical focus.

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3.3 Feasibility Studies of Industry Cases (WP 3)

Melkøya. Photo: Helge Sunde NTB/Samfoto

3.3 Feasibility Studies of Industry Cases (WP 3)

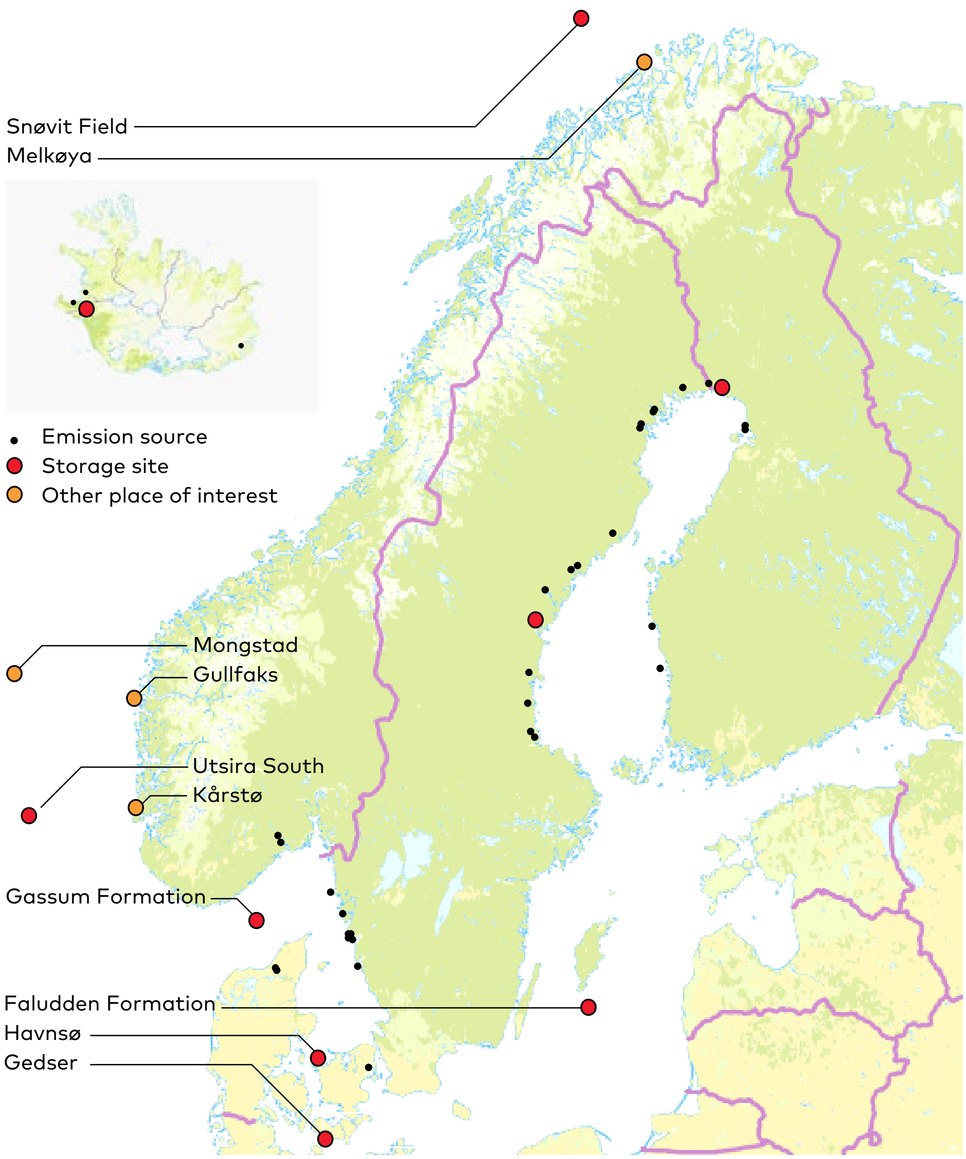


Figure 9. Overview over emission clusters and storage places selected as start-up cases.

3.3.1 Highlights

CCS case synthesis

The Nordic region is dominated by scattered sources, typically with emissions from 350 – 1,000 kt CO_2 annually, with potentially long transport distances to identified storage sites. WP 3 in NORDICCS has investigated different CCS cases in the Nordic region. The six CCS cases cover a wide range in CO_2 volume, industry sectors, distance between sources, number of sources, and distance to storage. There are many site-specific parameters influencing the cost estimation results. This makes it difficult to draw general conclusions. Figure 9 gives an overview over the locations of the sources (black and red circles) and possible storage areas (orange circles).

Transport and storage are necessary parts of the CCS chain, but the capture cost is the dominating cost element. The cost of capture is predominantly

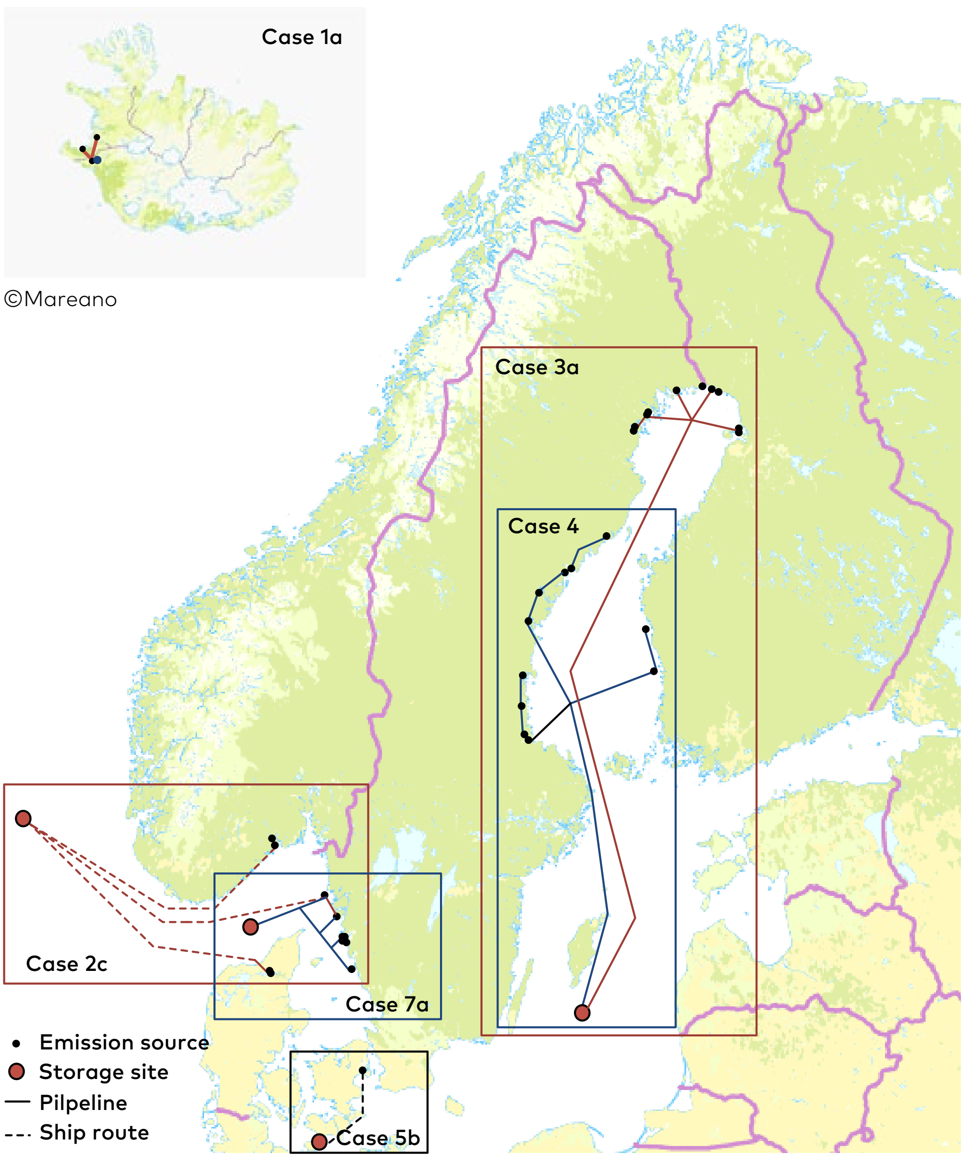


Figure 10. An overview of the six cases

1) Iceland
2) Skagerrak
3) Bay of Bothnia
4) Sweden and Finland
5) Copenhagen
6) Lysekil

dependent on the CO_2 volume. The capture cost, with the assumptions made in NORDICCS, lies in the region of 55-90 €/t CO_2. The wide cost distribution is mainly due to the variation in CO_2 volume and to some extent CO_2 concentration of the flue gas.

The seemingly most challenging geographical region is the Bay of Bothnia (see Figure 10 for case overview). This is due to long distances to storage. Finland has no identified potential CO_2 storage sites, and therefore captured CO_2 will have to be transported to Faludden in the Baltic Sea, or even further.

The transport costs depend mainly on the CO_2 volumes and the transport distance, and generally lie in the region of 12-20 €/t. For most cases, it was found that a ship-based transport network was the least costly solution. Transport over long distances favours ship options over pipelines. While the operational cost is higher for ships, shipping is more

Figure 11. Different transport solutions (dotted lines show ship routes, solid lines show pipeline routes).

- Emission source
- Storage site
- Pipeline transport
- Ship transport

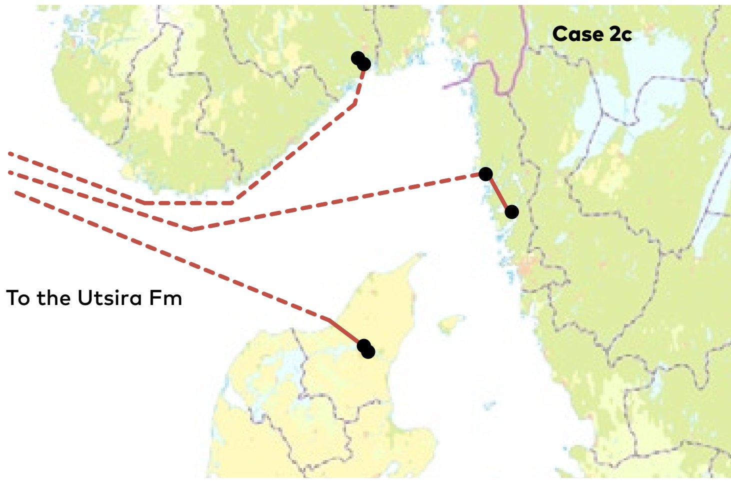
flexible than pipeline transport. Flexibility of transport is likely to be needed as there are large uncertainties when it comes to the time-frame of implementation of CCS for individual CO_2 emission points, and also due to uncertainties in storage capacities. There are few cluster benefits when considering ship transport, however, cooperation on storage is necessary in order to reduce the storage costs.

Several transport solutions have been investigated in the different cases. Figure 11 shows how the same sources can be used to create several different transport solutions.

In general, storage costs have been proven hard to obtain, and a complicating factor is that the cost is site specific. Still, an effort was made to combine storage costs provided by ZEP and the storage sites identified in the NORDICCS project to give an indication of the storage cost. The cost level was suggested from 7 €/t for the most developed fields (i.e. Utsira formation), to 20 €/t for the storage reservoirs with less information. This difference in storage costs between the sites proved to have an impact on the transport route of the CCS chain. For the cases where the Utsira formation was considered for storage, it was found that even though another storage site were located closer, storage at Utsira was still the most cost optimal solution for the chain. The reason for this is that transport distance is of less importance when ships are utilized, meaning that the CO_2 could be transported further if the storage cost for this site is lower.

The results from the six cases show a great difference in capture, transport and storage costs. In particular, capture costs have a huge span, as the cost will vary with several parameters, i.e. concentration of CO_2, volume of flue gas, and also local factors. Location factors are described as factors that will reduce the efficiency or expands the costs. Examples for such parameters is if the emission source is located in a remote area, if there are special weather conditions, explosion areas or if the source is in a high-cost industry like oil and gas.

Table 1 shows the cost for CCS for the six cases, with both a generic cost for the capture, and also the capture cost where local conditions have been accounted for. One solution for transport and storage is also presented.



Case	Description	Capture cost (€/t) (including location factor)	Transport cost (€/t)	Preliminary storage cost (€/t CO_2)
Case 1: Iceland	Relatively small CO_2 emission sources, approx. 900 kt CO_2/year from 4 sources.	42 – 140 €/t CO_2 (53-172€/t CO_2)	Onshore pipeline to Hellisheiði, 9 €/t CO_2.	Onshore storage in nearby basaltic rocks*, 13 €/t CO_2 (*water and gas injection from CarbFix)
Case 2: Skagerrak	6 emission sources around the Skagerrak Basin (Norway, Sweden and Denmark), approx. 6 800 kt CO_2 /year.	54 – 69 €/t CO_2 (59-86€/t CO_2)	Ship transport to Gassum reservoir, 15 €/t CO_2.	Gassum reservoir 14 €/t
Case 3: Bay of Bothnia	14 000 kt CO_2/year from 11 sources located both in Sweden and Finland.	58 – 68 €/t CO_2 (80-91€/t CO_2)	Pipeline to Faludden reservoir, 18 €/ t CO_2.	Faludden reservoir 16 €/t
Case 4: Sweden and Finland	11 emission sources around the Gulf of Bothnia, approx. 10 400 kt/year CO_2.	59– 66 €/t CO_2 (70-105€/t CO_2)	Pipeline to the Faludden reservoir, 13 €/t CO_2.	Faludden reservoir 16 €/t
Case 5: Copenhagen, Denmark	A single emission source, approx. 1 500 kt CO_2 /year.	65 €/t CO_2 (68 €/t CO_2)	Ship transport to Havnso reservoir, 5 €/t CO_2.	Havnso reservoir 20 €/t
Case 6: Lysekil, Sweden	Approx. 4 600 kt CO_2 /year from 6 Swedish sources	58 – 101 €/t CO_2 (68-140€/t CO_2)	Combination ship/Pipeline to Gassum reservoir, 12 €/t CO_2.	Gassum reservoir 14 €/t

Table 1. Cost results from the case studies.

The large CO_2 volumes in the Bay of Bothnia pose a challenge due to the lack of storage sites in the region. Onshore transport to the Barents Sea is a challenge both technically and politically, and is therefore not considered further. The Faludden formation is not expected to be able to store all the CO_2 from sources around the Bay of Bothnia. It is therefore likely that CO_2 from this region would need to be transported to the Gassum formation or even further, to the Utsira formation.

The Nordic region is in a favourable position to cooperate on CCS. The large CO_2 sources from industry in Sweden and Finland, and the great storage possibilities in Norway can stimulate the creation of CCS networks. Iceland has smaller CO_2 emission sources, but promising onshore storage possibilities.

Recommendation for R&D in the Nordic region

To promote CCS implementation in the Nordic countries, focus must be on developing CO_2 capture technologies with acceptable energy penalty. Individual considerations are needed for each industry sector, and maybe even for each individual site. Post-combustion technologies seem to be the best short-term solution for existing plants. Further R&D may qualify low-energy absorbents/ adsorbents, other novel gas separation technologies and cryogenic technologies to improve the efficiency and reduce the cost. Efficient capture of biogenic CO_2 emissions and innovative concepts can provide carbon negative solutions, and should be developed.

Even though both pipeline and ship transport of CO_2 are established today, development of an optimal CO_2 network and infrastructure as part of the CCS chain is a challenge in the Nordic countries. Large-scale transport solutions will likely combine ship and pipeline transport. Technology development is needed for offshore unloading of CO_2 from ship for injection into geological storage formations. There are uncertainties regarding the effect that impurities in the CO_2 stream could have on transport and storage. Better thermodynamic data for impure CO_2 is needed to identify and quantify potential negative effects related to critical impurities and recommended limits.

Long-term, safe, reliable and publicly acceptable offshore CO_2 storage is crucial for Nordic CCS deployment. For many of the identified storage sites, more and better data are needed to understand storage mechanisms, dynamic CO_2 reservoir behaviour as well as suitable monitoring techniques and mitigation measures in the event of CO_2 leakage. More injection pilots should be set up to build knowledge needed for injection well design and location. Particularly the promising Faludden and Gassum formations should be investigated to reduce uncertainty in injectivity and storage volume. CO_2-driven EOR is still an opportunity in the North Sea, which potentially could change the economics of CCS in a positive direction, and warrants further considerations.

In order to close many of these knowledge gaps a closer cooperation between academia/research institutes, national governments and the various industries and power producers is required. Finding adequate incentives to promote such cooperation projects is therefore essential.

3.3.2 Description of Activities

Based on the findings from the NORDICCS work packages on capture, transport and storage, a number of CCS cases were identified for the feasibility study. Six industrial sources were studied in detail, and these were the bases for the fully integrated CCS cases investigated in the feasibility study.

In addition to the feasibility study, a report addressing CCS knowledge gaps as well as recommendations and innovation in the Nordic countries was performed.

This work was executed through discussion and workshops with partners representing the other work packages. Two workshops were held exclusively for this work, but also attending the group meetings and conference has given valuable input to the reports.

3.3.3 Industry Benefits

To prepare Nordic industries and fossil-based energy producers for future deployment, CCS will play a vital role in sustainable development. Through focused R&D and large-scale demonstration projects, competence and experience are being developed. This provides a good platform for efficient, safe and successful implementation of CCS. For each industry, information regarding cost and technology options for a particular site can provide valuable input for preparing for CCS. By conducting studies and investigations, including site-specific information, a more realistic and optimal capture and transport route can be obtained. This investigation gives information on different options, and may be a starting point for further investigation of CCS chains. Cluster benefits have also been evaluated, and especially for storage cost, cooperation between different sites to increase the volumes is important.

By maintaining and improving our CCS competence, the Nordic countries will be prepared to face the needs as the CCS industry establishes and grows. Political courage and political will must provide a predictable framework to overcome current barriers and make CCS happen.

NORCEM Cement plant, Brevik, Norway. Photo: Norcem

3.4 CO_2 Capture (WP 4)

3.4.1 Highlights

Nordic point-source emissions are dominated by heat and power generation, pulp and paper production, oil and gas refining, and iron and steel production. The total CO_2 emissions from facilities emitting more than 100,000 tons per year reached almost 153 Mt in 2011. The distribution of the largest Nordic industrial point-source emissions are illustrated in Figure 12.

The technical feasibility of implementing CO_2 capture in the major heavy industry sectors in the Nordic countries has been evaluated. The cases were chosen to represent the sectors responsible for the largest point source CO_2 emissions in the Nordic countries. This undertaking shows that it can be feasible to apply retrofit CCS to a range of industry sectors with different process conditions.

No known CO_2 capture technology holds a clear advantage over others, but results show that it remains crucial to consider carefully the individual process and site- specific conditions on a case-to-case basis as these strongly affect the capture technology performance, and thus the most feasible choice of technology. It must also be taken into consideration that possible developments in the respective core industrial processes can further simplify CCS implementation and improve the CO_2 capture efficiency.

The specific outcome of the case studies for cement production and oil and gas refineries show that internal differences within the processes and between the different process streams greatly affect the suitability and feasibility of CO_2 capture. Implementation of CO_2 capture can also affect future development of the core processes such as in iron and steel production and in pulp and paper production.

Although none of the technologies stand out as the preferred choice, post-combustion absorption of CO_2 from flue-/process gases has two major advantages; it may be applied as an end-of-pipe technology affecting the core process operation to a very small degree, and it is commercially available and has been used industrially for natural gas sweetening for decades. For processes with lack of excess heat, oxy-fuel combustion may be a good alternative as this technology is driven by power, not heat.

3.4.2 Description of Activities

Five case studies were developed for case specific sites under conditions relevant to the Nordic region in order to assess the technical feasibility of CO_2 capture implementation. The results from the technical evaluation were used as basis for economic feasibility studies developed in WP 3.

Detailed process models were developed for iron and steel production, cement production, pulp and paper production, and oil and gas refineries. In addition, the technical potential for CO_2 capture from geothermal power production in Iceland was evaluated. Due to the strong focus on industry implementation, heat and power generation was excluded from the assessment.

State-of-the-art CO_2 capture technologies were evaluated and the choice of technology was made based on the nature of each core industrial process under consideration. Technologies assessed in the technical case studies include post-combustion absorption with monoethanolamine (MEA), pre-combustion capture with Selexol and Rectisol, oxy-fuel combustion, water absorption and low-temperature (cryogenic) separation. A CO_2 capture rate of 85% was applied in all the case studies, except for the case of geothermal power generation in Iceland, where this was considered as a variable. The geothermal case differs considerably from the other cases as the flue gas composition is very different and as separation of H_2S becomes an additional part of the problem. A summary of the individual case studies is presented below.

Figure 12. Nordic industrial CO_2 emissions by sector (> 100 000 t/a) for 2011. CO_2 emissions from pulp and paper production include biogenic emissions as well as fossil emissions.

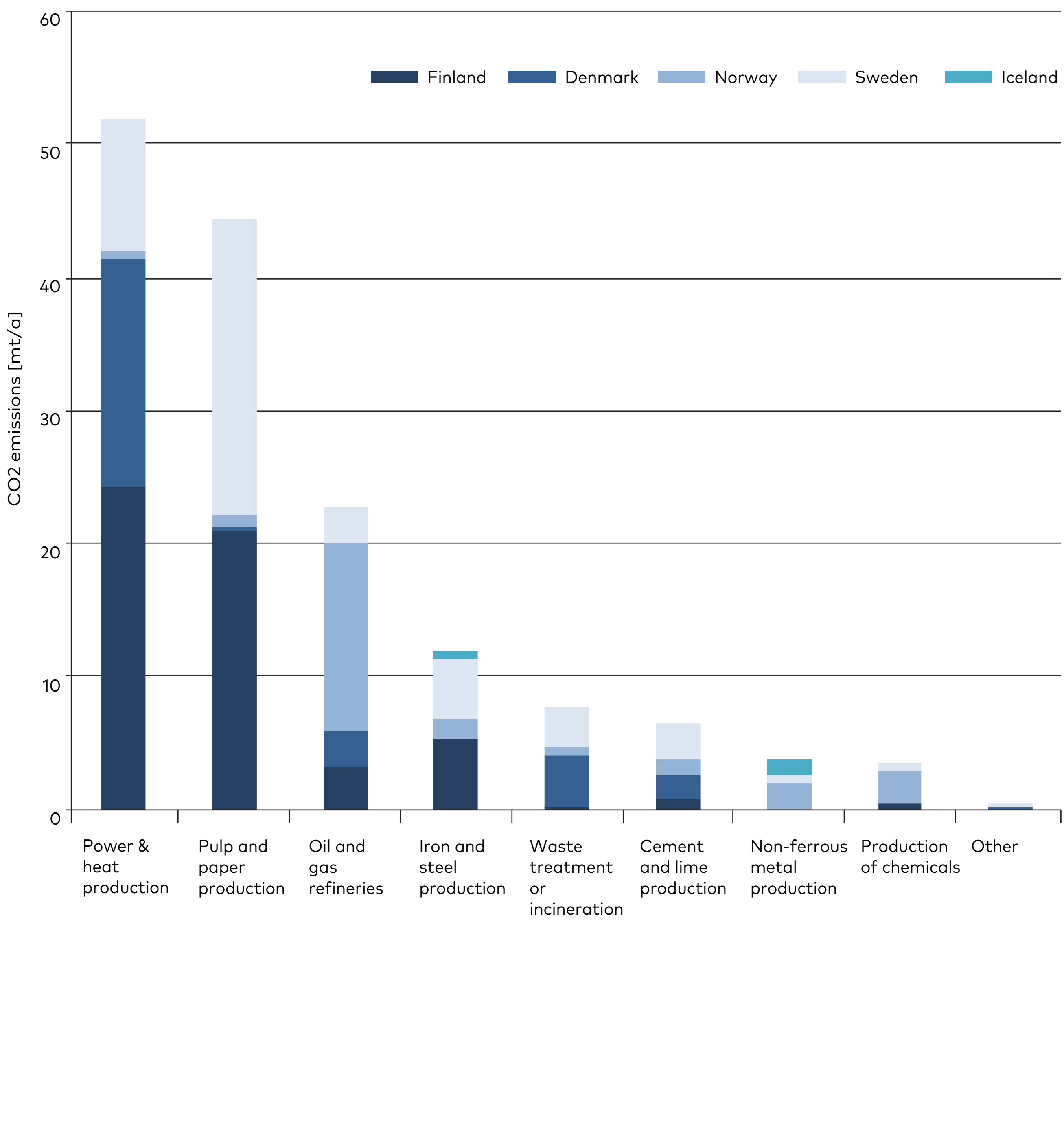
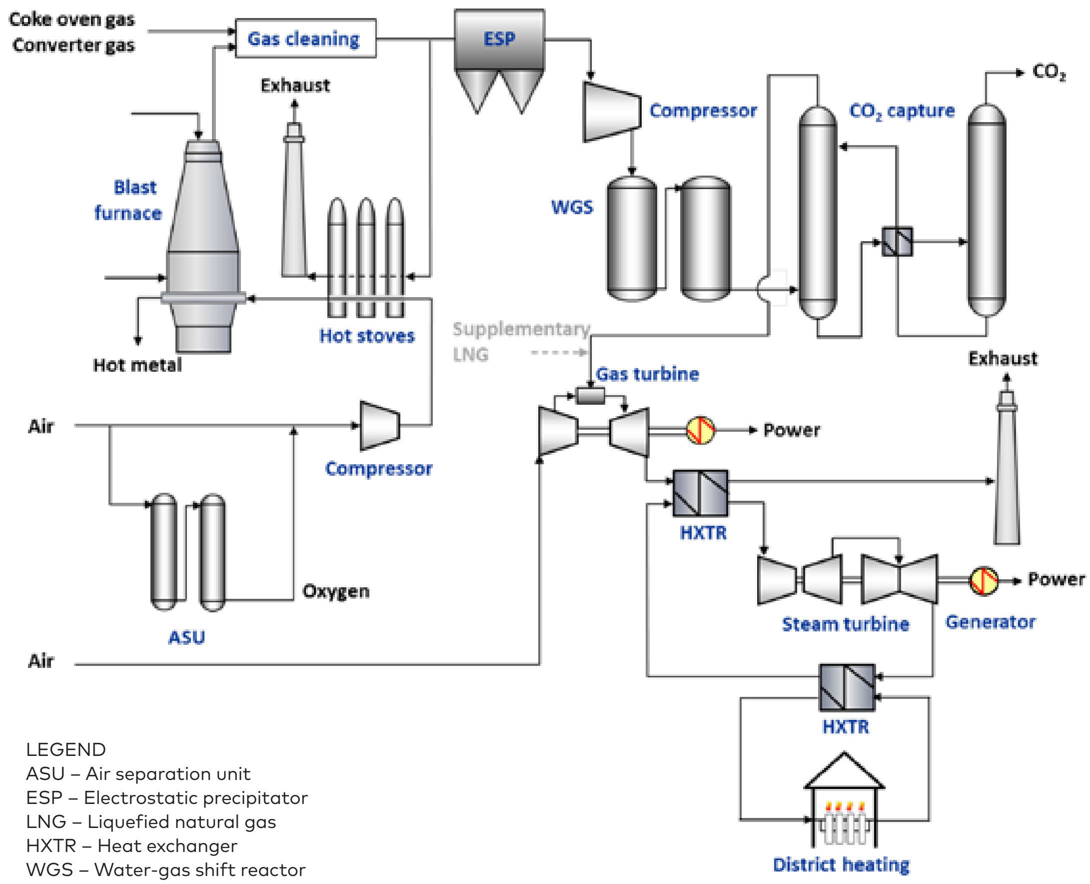


Figure 13. Modified blast furnace process with CO_2 capture.



LEGEND
ASU – Air separation unit
ESP – Electrostatic precipitator
LNG – Liquefied natural gas
HXTR – Heat exchanger
WGS – Water-gas shift reactor

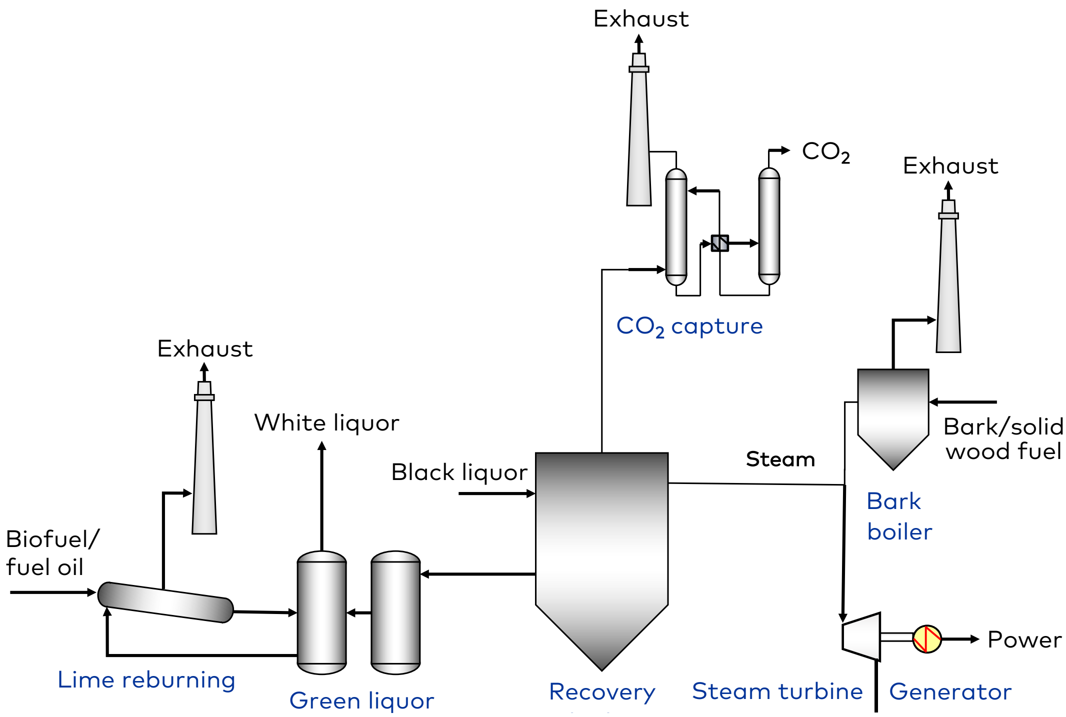
CO_2 capture in iron and steel production

Steel is produced by refining iron extracted from an iron ore in a reducing atmosphere in a blast furnace. The addition of carbon, usually in the form of coke, is needed to create the reducing environment. Consequently, CO_2 emissions from the iron and steel production originate both from iron making and from combustion processes. Heat and power to the steel production is generated in an onsite power plant fuelled by process/exhaust gases from the iron and steel mill.

In this case study, a concept of increasing the blast furnace top gas (exhaust gas) calorific value for more efficient power production on site has been evaluated. By replacing part of the reducing agent coke with increased pulverized coal injection (PCI) and an oxygen blast furnace, the blast furnace top gas achieves a calorific value that enables combustion in a high-efficiency combined cycle gas turbine combined cycle (GTCC). The GTCC has significantly higher fuel conversion efficiency than the conventional gas boiler power plant. Pre-combustion capture of CO_2 based on amine and Selexol absorption was investigated. This further increases the top gas heating value and enables removal of CO_2 from the steel production. The evaluated process is illustrated in Figure 13.

Results show that the effects of the modifications include decreased coke consumption, reduced CO_2 emissions and increased onsite power production except in the MEA case where additional input of fuel is needed to heat the desorber reboiler. The modified concept with Selexol pre-combustion capture proved to be the most viable option with the largest reduction of direct CO_2 emissions and the lowest parasitic load on the core production process.

Figure 14. Cement production process with post-combustion CO_2 capture.



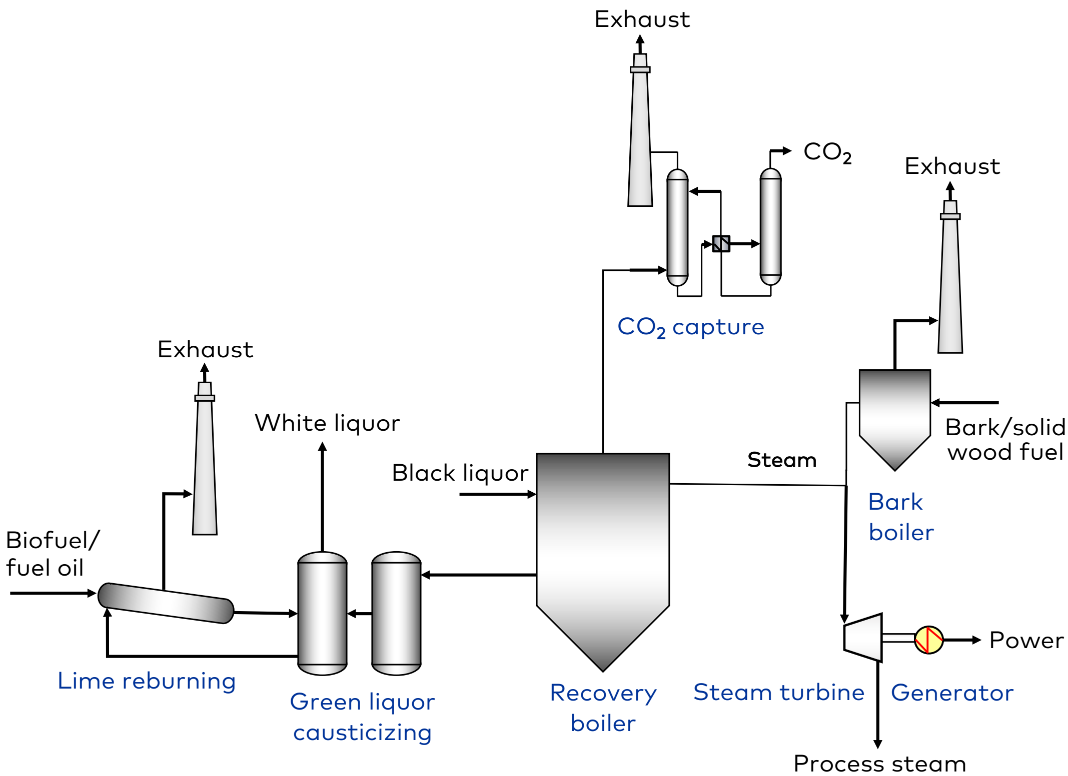
CO_2 capture in cement production

The case study for retrofitting CO_2 capture into a cement production plant was developed for the Norcem Heidelberg Cement plant in Brevik, Norway. Cement is produced by heating limestone in a rotary kiln in order to reduce it to calcium oxide. A by-product of this reduction process is CO_2. As a consequence, CO_2 emissions from cement production originate both from cement production and from onsite combustion processes. The cement production process with post-combustion CO_2 capture is illustrated in Figure 14.

In this case study, two options were assessed: retrofit post-combustion capture based on amine absorption from the exhaust gases and oxy-combustion. Compared to oxy-combustion the amine post-combustion option requires fewer modifications to the existing cement plant. Major modifications include the addition of waste heat burners for recovery of waste heat and possibly exhaust gas treatment (NOx, SOx and dust). Energy required for CO_2 capture is supplied from exhaust gas waste heat and a dedicated energy plant. CO_2 from the energy plant is also assumed to be captured, leading to a larger CO_2 capture plant than if only the CO_2 from the cement plant is captured.

Retrofitting the plant with an oxy-combustion system would, in addition to new design for existing units, require additional processes. This could be: an air separation unit for oxygen production, a CO_2 compression and purification unit (CPU) for processing flue gas, and a recirculation system to recycle part of the flue gases back to the lime kiln in order to control the combustion temperature. Reduction of air in-leakages would be critical. Evaluations of the electricity consumption of oxy-

Figure 15. Overview of the pulp mill chemical and energy recovery system.



combustion technologies identified the CPU as a major consumer, and the amount of air in-leakage is an important factor for the CPU performance. The CO_2 reduction potential for the oxy-combustion option is similar to the amine post-combustion.

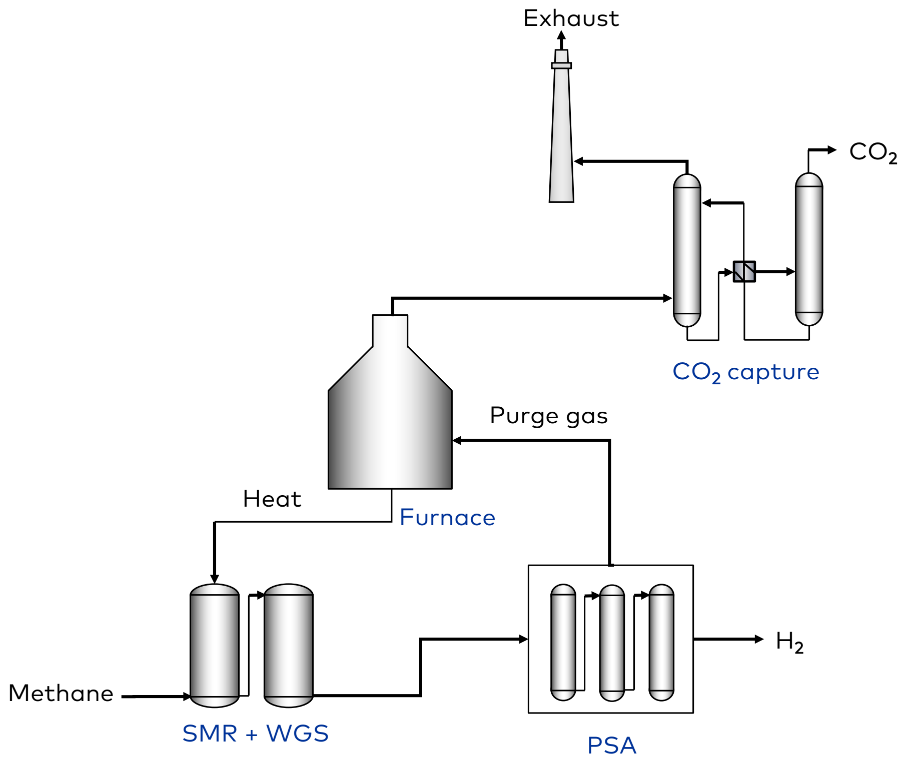
CO_2 capture in pulp and paper production

The case study for retrofitting CO_2 capture into a pulp and paper production plant was developed for the Östrand pulp mill in Sweden. Pulp is made by cooking wood chips in a chemical mixture. After cooking, the pulp is removed and further processed while the spent cooking liquid (black liquor) is combusted in the recovery boiler where inorganic pulping chemicals are recovered while organic dissolved material is combusted in order to generate steam and electricity. The pulp mill chemical recovery cycle is illustrated in Figure 15.

In this case study, three options were assessed for CO_2 reduction from pulp and paper production: post-combustion amine absorption from the recovery boiler (no changes in the chemical recovery system), black liquor gasification combined with Selexol pre-combustion for electricity production and black liquor gasification with Rectisol pre-combustion for motor vehicle fuel (dimethylether, DME) production.

Results show that for the recovery boiler case, implementation of CO_2 capture has significant consequences on the overall balance of the process. In order to generate steam for the CO_2 capture process large amounts of additional fuel was burnt in the bark boiler, resulting in additional electricity production. For the black liquor gasification case with electricity production, results showed rather low additional utility consumption, with the exception of electricity usage. The additional resource consumption associated with CO_2 capture using the Rectisol process was shown to be the lowest of the three

Figure 16. Schematic of the hydrogen production process with the integrated post-combustion CO_2 capture unit.



scenarios and since only a CO_2 compression section prior to transport would be required, the investment cost for the third scenario is lower than for the other two options.

The recovery boiler case has a significantly larger amount of emissions originating from biomass. The potential effect on global CO_2 emissions by applying bio-energy with CCS (BECCS) was the highest in this scenario.

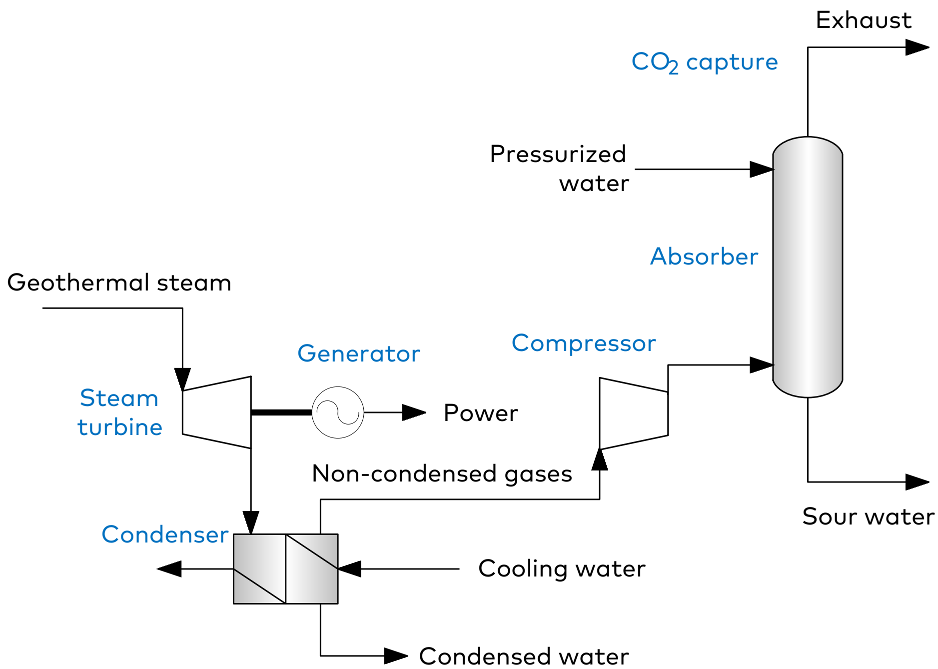
The large amount of emissions originating from solid wood fuels in the black liquor case for DME production, is due to the fact that energy contained in the black liquor cannot be used to satisfy the demand for heat and electricity in the pulp mill. Instead, it leaves the system in the form of DME. As a consequence, additional fuel and electricity has to be purchased from an external source to satisfy the demand.

CO_2 capture in oil and gas refineries

The case study for retrofitting CO_2 capture into an oil and gas refinery was developed for the Preemraff Lysekil refinery in Sweden. The Lysekil site is a relatively complex refinery and includes a number of processing units and the CO_2 emission in the refinery is collected and released from several platforms greatly varying in flue gas composition.

In this case study, partial CO_2 capture from the hydrogen production, crude and vacuum distillation (process heaters) and the fluid catalytic cracker (FCC) was evaluated. Both amine and ammonia post-combustion capture was assessed. The hydrogen production process with post-combustion CO_2 capture is illustrated in Figure 16.

Figure 17. Simplified process flow diagram of part of geothermal plant with CO_2 and H_2S capture.



Results show that the ammonia process is more favorable from the viewpoint of heat requirement. A significant part of the CO_2 capture process heat demand can be covered by waste heat, and thus there is not a drastic decrease in the net capture rate on a plant level when emissions from an external energy plant utilizing natural gas is considered. One advantage when implementing CO_2 capture into an oil and gas refinery is that there is typically an abundance of excess heat available. A drawback regarding the refinery is that it consists of several CO_2 sources, where the CO_2 concentration varies between 5 and 50%, and even though the hydrogen production unit is the single largest point source at the refinery, it only accounts for roughly 30% of the total refinery emissions. The refinery also includes CO_2 sources that are not suitable for CO_2 capture, mainly due to their relatively small size. As a consequence, the overall capture efficiency of the refinery will be below the 85-90% capture rate that is possible to achieve for an individual stream. It is also important to remember that CO_2 emissions from the end-use of the oil products are of even greater concern than the process emissions from the refining industry.

CO_2 capture in geothermal power generation

The case study for retrofitting CO_2 capture into geothermal power generation was developed for the Hellisheiði Geothermal power plant in Iceland. The plant cogenerates power and hot water for district heating. Geothermal steam is not pure H_2O, but also contains H_2S, CO_2, H_2, N_2 and CH_4.

In this case study, four different capture systems for co-removal of CO_2 and H_2S were assessed: water absorption, amine absorption, amine-low temperature hybrid concept and standalone low-temperature separation. The power production process with CO_2 capture is illustrated in Figure 17.

For co-removal of H_2S and CO_2, low-temperature separation seems to be an attractive alternative to the conventional water absorption process due to low power penalty. Ultimately, the energy calculations must be complemented by cost estimations to get a more complete basis for comparing the different technologies.

3.4.3 Industry Benefits

Results from the case studies show that it can be feasible to implement retrofit CO_2 capture technologies to Nordic industry sectors. However, it is crucial to take into account site and process specific conditions, which strongly affect the choice of technology, in turn allowing for increased CO_2 capture efficiency and reduced costs. No capture technology stands out as a first choice, although amine post-combustion has the advantage of being an end-of-pipe solution that is already commercially available.

The evaluations made for cement production and oil and gas refining show that there are important process-specific differences that strongly affect the suitability to separate CO_2 from different process streams, and the case studies on iron and steel and pulp and paper production show that the implementation of specific capture technologies may affect the favored development of the process.

When implementing CO_2 capture, the most important challenge and difference between an industrial process and heat and power generation, is the typical lack of excess heat for solvent regeneration in the former process. To acquire and operate a unit to generate heat on a scale of hundreds of megawatts requires a significant investment. This fact may in turn favor technologies like oxy-fuel combustion, which mainly is driven by power rather than heat.

3.5 CO_2 Transport (WP 5)

CO_2 carriers Yara Frøya and Yara Gerda at the Terminal of Tees, England. Photo: Yara International ASA

3.5 CO_2 Transport (WP 5)

3.5.1 Highlights

When comparing cost for CO_2 transport by ship and by pipeline, ship transport has been found to be the least costly transport option in the Nordic region, not only for most of the individual sources but also for most of the investigated potential clusters during a ramp-up phase. The main reason for this is the combination of moderate CO_2 volumes and long transport distances. It can also be observed that poor injectivity in the reservoirs in the Baltic Sea together with the fact that ship transport cost only increases modestly with increasing distance, may in fact render it less costly to transport the CO_2 from sources around the Baltic Sea by ship a further 800-1,300 km to the west to storage in reservoirs in the Skagerrak region or in the North Sea.

Two of the main challenges when modelling CO_2 pipelines are to predict temperatures during the emptying of a pipe, and to assure that running fractures cannot occur. Modelling fractures requires accurate knowledge of the speed of sound, which is not available for all CO_2 mixtures. Results show that CO_2 pipelines may be more susceptible to running fractures than natural gas pipelines, so accurate modelling is necessary. To stay within the design temperature range of the pipeline, low temperatures during e.g. the emptying of a pipe should be avoided. Simulations show that impurities like nitrogen and oxygen increase the boiling temperature, which can actually be beneficial when it comes to avoiding low temperatures. Finally, existing simulation tools for CO_2 pipelines are not yet mature, and needs further development based on better experimental data, such as for viscosity and density.

3.5.2 Description of Activities

Recommendations on CO_2 transport solutions (Task 5.1)

This part of the work involved analysis of feasible CO_2 transportation options in the Nordic region. In 2010, there were 284 sources emitting 100 kt CO_2 or more (biogenic or fossil) in the Nordic countries. Stationary CO_2 sources in the Nordic region are characterized by relatively modest emissions, coastal or near-coastal location and long distances to potential storage sites (most sources emit between 100 kt up to 1 Mt CO_2 per year and are located 300 km and more from a potential storage site). Since most of the large-scale CO_2 emission sources in the region are located close to or along a coastline, both ship and pipeline are feasible transport options. Hence, this part of the work focused on cost analysis comparing cost for ship and pipeline transport. The analysis was carried out in five different ways:

1. Cost of pipeline and ship transport was compared as a function of volume and distance.
2. The pipeline volumetric break-even point and the associated cost was calculated for transport from eight selected sites to three selected reservoirs in the region assuming that a CO_2 hub could evolve at each of these sites.
3. Specific transport cost was also calculated for six plants individually.
4. It was analyzed what effect reservoir injectivity may have on the choice of reservoir in the Nordic region and thus also on the transportation mode.
5. The effect on cost from underutilization of pipelines was calculated.

In the first exercise, cost for pipeline and ship transport was compared for volumes ranging from 0.5 to 20.0 Mtpa (million tons per annum) being transported between 50 and 1,200 km. The calculations showed that ship transport will be the least costly individual transport option for 45 out of the 55 largest sources located along the coastline. Moreover, these calculations also showed that ship transport cost only increases modestly with increasing distance.

The pipeline volumetric break-even point identifies the CO_2 volumes that will be required for pipeline to be the least costly transport option over a given transport distance. Thus, the least costly transport mode from the eight anticipated hub locations was defined for any combination of clusters transporting CO_2 to the selected storage site. The eight hubs were selected so as to represent a reasonable geographical distribution of the large-scale CO_2 sources in the Nordic region. Figure 18 shows the pipeline volumetric break-even point along with associated cost for the eight selected hub sites. Also shown are the selected storage site and the corresponding transport distance for each hub location. It should be noted that size and shape of the storage sites given in Figure 18 is illustrative only.

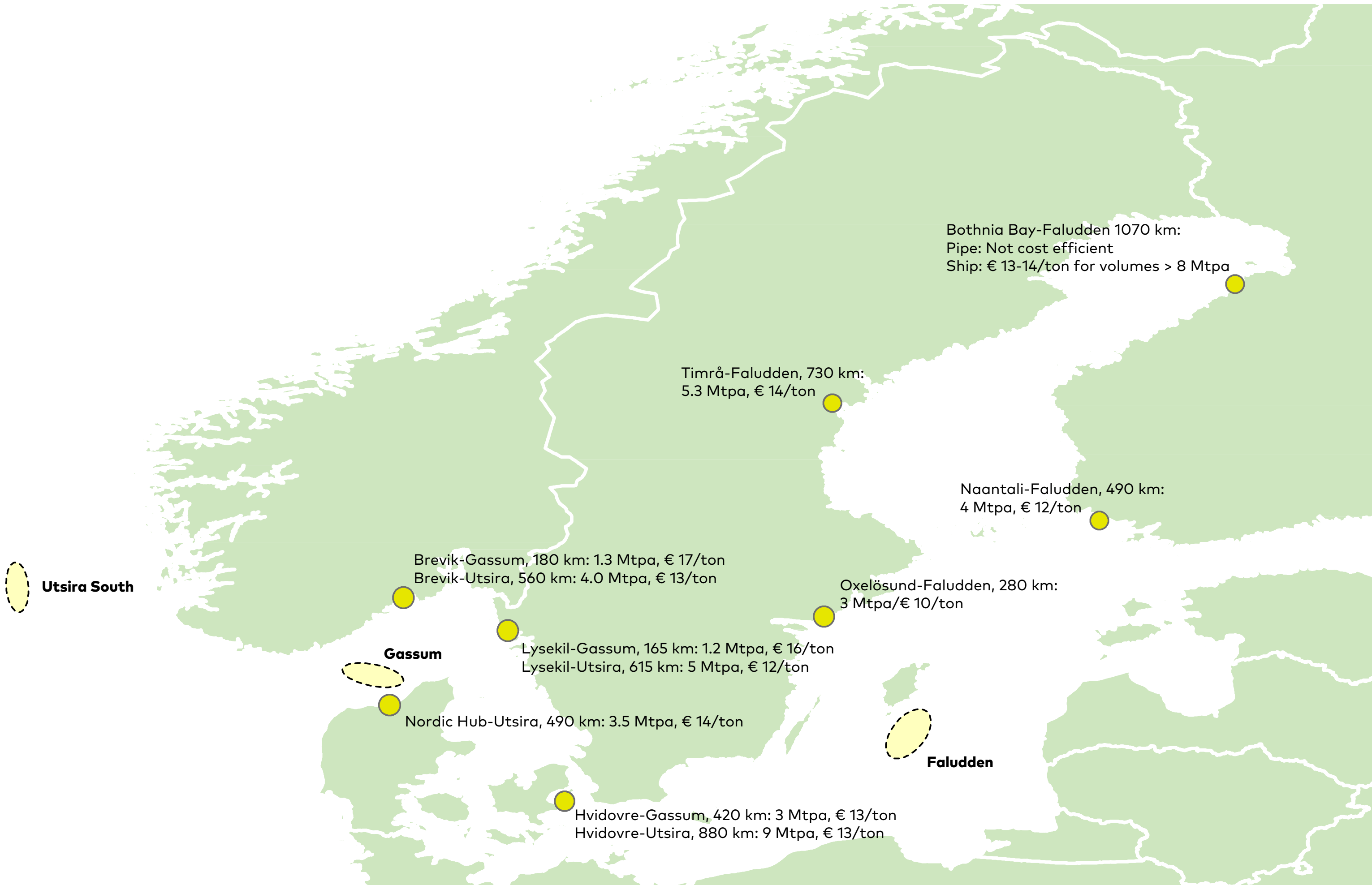
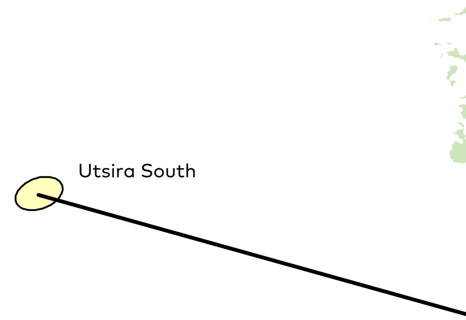


Figure 18. The figures in the map give the pipeline volumetric break-even point in Mtpa and associated cost for eight potential CO_2-hubs (yellow circles) in the Nordic region. Also shown are the three selected storage sites (light yellow ellipses); Faludden, Gassum and Utsira south.

Figure 18 indicates that pipeline could be a feasible transport mode for three out of the four selected sites located along the Baltic Sea provided 1) that sufficient CO_2-volumes can be reached which will require that the CO_2 is collected from multiple sources and 2) that reservoirs in the Baltic Sea can be utilized for storage. In other words, if reservoirs in the Baltic Sea fail to provide sufficient injection and/or storage capacity, the CO_2 must be transported further west, either to reservoirs in the Skagerrak region or in the North Sea, in which case ship transport will provide the least costly transport option.



Specific transport cost both by ship and by pipeline to the closest located storage site was calculated individually for six large emission sources (the two northernmost and four westernmost located sources in Figure 18). In four of the cases ship transport was found to be the least costly transport option with specific cost ranging from 14 €/t from Avedøreverket coal power plant in Hvidovre to 22 €/t from Norcem cement plant in Brevik, in both cases to the Gassum formation in the Skagerrak region. The reason that transport cost is higher from Norcem's cement plant than from Avedøreverket coal power plant, in spite of 240 km shorter transport distance (see Figure 18), is that the transported volume is much lower; 0.7 Mtpa in the Norcem case versus 2.5 Mtpa in the Avedøreverket case. For two of the cases, Preem's refinery on the Swedish west coast and the assumed Nordic hub on the Danish Northwest coast, pipeline has been calculated to be the least costly transport option, with specific cost ranging from 13 €/t in Preem's case to between 16-25 €/t from the Nordic hub depending on applied storage site (Gassum or Utsira). The results also show that pipeline transportation cost may decline drastically for sources located in the Skagerrak region if the volumes could be increased, i.e. include more sources, from for instance 4 €/t for 5 Mtpa being dispatched from Preem, Lysekil to 11 €/t for 2 Mtpa being dispatched from Norcem, Brevik, in both cases to the Gassum formation. Figure 19 shows the various pipeline transport systems analyzed in the Kattegat-Skagerrak region.

For any reservoir, there is an optimal CO_2 injection volume, i.e. optimal with respect to full utilization of the reservoir's storage capacity. The optimal injection volume is usually not known and will be specific for each individual reservoir, i.e. each reservoir is likely to have a specific optimal injection strategy with regard to well locations and well injection volume. In addition, drilling of so-called water producers (for pressure management) will be essential in order to utilize as much as possible of the reservoir's storage capacity. At the same time,drilling of offshore wells is expensive and hence, the chosen injection strategy will probably need to be balanced between cost and requirement for storage and injection capacity.

Little is known about the storage capability of the reservoirs in the Baltic Sea. Nevertheless, dynamic modelling and simulated injections suggest an injectivity between 0.5 and 1.0 Mtpa per well in the Faludden aquifer, and that water producing wells may also be required. Since the drilling of offshore injection wells and water producing wells represents high costs while, as aforementioned, cost for ship transport increases relatively slowly with increasing transport distance, it is interesting to analyze the potential effect injectivity may have on the choice of storage reservoirs in the Nordic region. Thus, transportation cost was calculated for four different assumptions on well injectivity (and consequently also on required number of wells and subsea templates) assuming that all cases transport 4 Mtpa of CO_2 by pipeline or by ship from Naantaali, Finland (see Figure 18). Assuming that annual well injection capacity refers to continuous injection (here assumed 8,760 hours per year yielding, for 4 Mtpa, 457 tons per hour), this obviously constitutes a problem for ship transport unless there is a permanent "injection barge" moored at the storage site. In order to include cost of injection, ship cost was calculated in two ways; 1) optimizing ship sizes in order to achieve

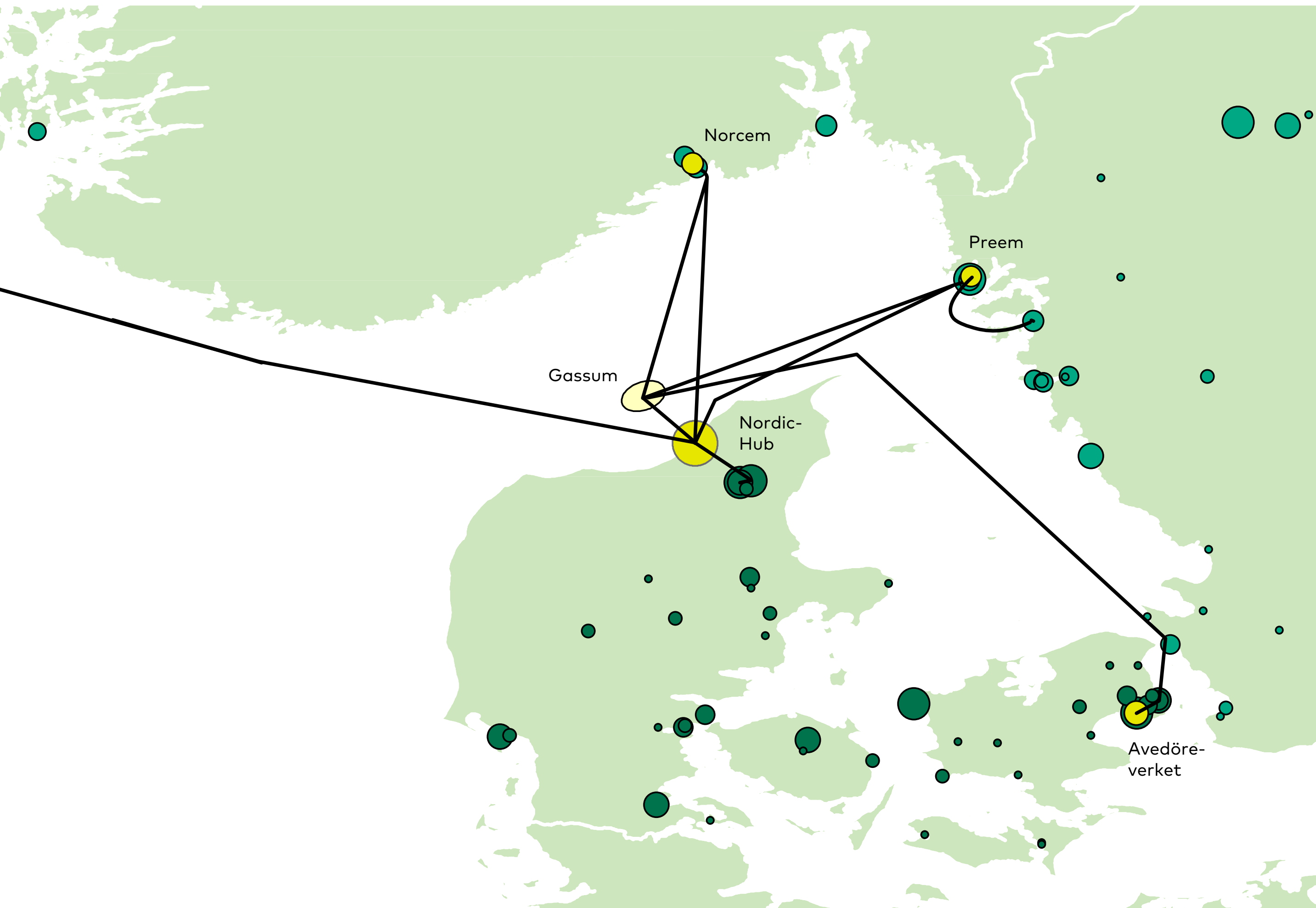


Figure 19. Analyzed transport systems in the Skagerrak region either directly from each country to the Gassum formation or via hub located in northwest Jutland to Utsira.

		Gassum (ship transport)			Utsira (ship transport)		
Assumed well injection	Pipeline	Manipulating	Injection barge	Injection barge	Manipulating	Injection barge	Injection barge
capacity, Mtpa	Faludden	Ship size	no STL	with STL	Ship size	no STL	with STL
0.5	28.5	37.1	37.0	37.4	38.4	35.4	35.8
1.0	19.5	27.6	25.4	25.8	28.4	26.8	27.2
2.0	15.7	22.1	22.0	22.4	25.6	22.6	23.0
4.0	13.7	19.3	19.2	19.6	23.7	20.7	21.1

Table 2. Specific cost (€/t) from Naantaali as function of injectivity (cost based on assumed drilling cost of € 50 million per well).

injection rates as close to the maximum as possible (to reduce "off-time" at the injection site as much as possible), i.e. close to 457 tons per hour, or 2) by installation of an injection barge with and without an STL (Submerged Turret Loading) at the storage site. The size of the injection barge is assumed the same as the size of the transport ship.

Table 2 shows specific transport cost for 4 Mtpa being transported by ship from the Naantaali site on Finland's Southwest coast to Faludden, Gassum and Utsira (see Figure 18) assuming different well injectivity levels in the three reservoirs.

As can be seen from Table 2, assuming a well injectivity of 0.5 Mtpa in Faludden indicates that it may be less costly to transport the CO_2 by ship a further 800 km to Gassum and 1,300 km to Utsira provided that at least 1 Mt can be injected per well and year in Gassum/Utsira, in particular if an injection barge is moored at the injection site. Increasing injectivity to 1 Mt per well and year in Faludden reduces cost significantly implying that at least 4 Mt needs to be injected per well and year in Gassum for Gassum to be the least costly alternative while even higher injection rates will be required at Utsira. Yet, at these injection levels, the difference in cost between the three storage alternatives is modest, with cost ranging from € 19.2 at Gassum to € 21.1 at Utsira if an injection barge is moored at the site versus € 19.5 at Faludden. Reducing drilling cost per well by 50% to 25 million Euros changes the results slightly. Assuming a well injectivity of 0.5 Mtpa in Faludden will require the use of an "injection barge" and an injectivity of 1 Mtpa per well in Gassum for Gassum to be the least costly alternative while at least 2 Mt will have to be injected annually per well in Utsira in combination with the use of an "injection barge". Assuming instead that 1 Mt can be injected per well and year in Faludden will require use of an injection barge and an injection capacity of 4 Mtpa and well in Gassum for Gassum to be the least costly alternative. In all, these observations underline the strong influence of the cost of drilling the wells which may be further emphasized if also water producers will have to be drilled.

A CO_2 transport system comprising multiple and clustered sources will probably require several years before becoming fully developed. Hence, the last exercise calculated the effect on specific cost for a pipeline carrying 10 Mtpa over 500 km as a function of the utilization ratio (25%, 50%, 75% and 100%) reaching 100% utilization after ten and five years, respectively. The calculations showed that specific cost will almost double, from 8.4 to 16.1 €/t if the pipeline has a 25% utilization ratio for the first ten years of operation as opposed to 100% utilization already from the start. Obviously, the effect on specific cost will be less significant if there is a shorter ramp-up period. In practice, the most cost efficient solution will have to be analyzed for each specific transport case bearing in mind that 1) it is not obvious who will carry the risk for a pipeline risking several years of underutilization and 2) one large single pipeline will probably have less impact on the surrounding environment than several smaller pipelines.

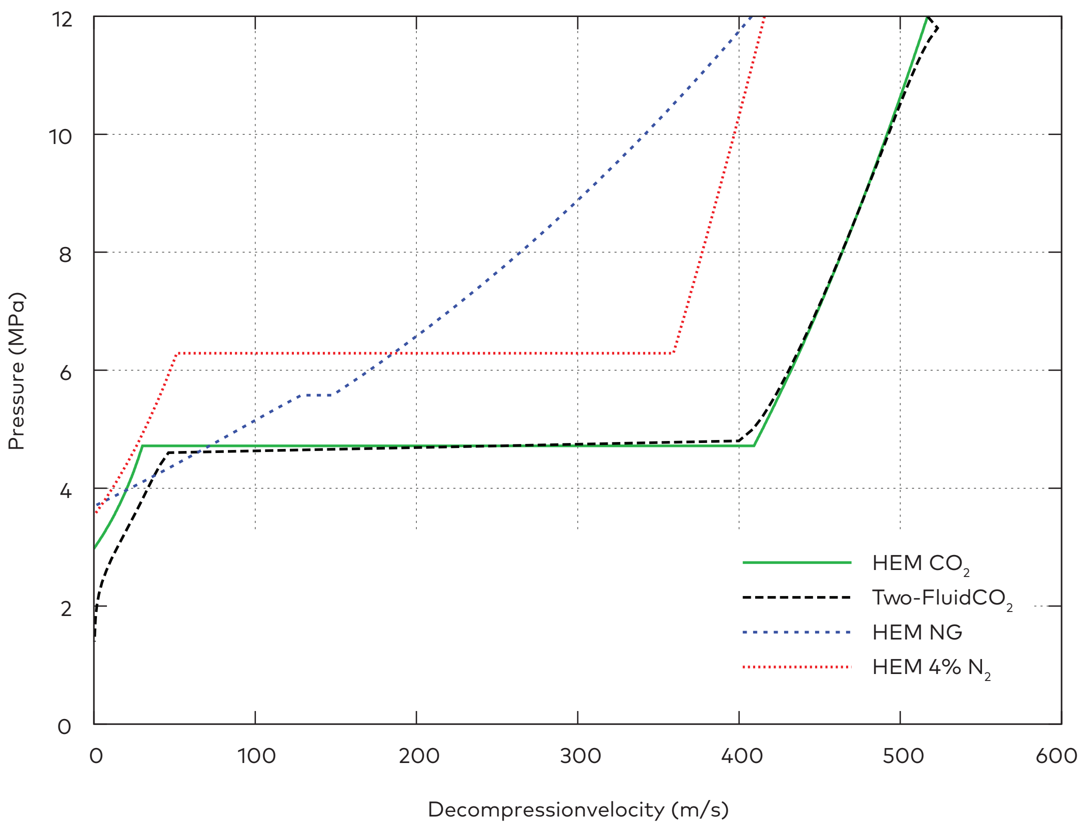


Figure 20. Decompression velocity for different models and mixtures. A lower curve will be less susceptible to running fractures. NG is natural gas, HEM is the homogeneous equilibrium model. The red line is for a mixture with 96% CO_2 and 4% nitrogen.

Impact of fundamental properties of CO_2 stream (Task 5.2)

The focus was on fundamentals of modelling and simulation of CO_2 pipeline flow with impurities. Such flows are inherently complex for a number of reasons. First, the mechanical and thermal interaction between a gas and liquid flowing can be somewhat chaotic. Second, advanced models are needed to describe the relationship between pressure, temperature and density in CO_2 mixtures. Third, the viscosity of the mixture can change significantly when small amounts of impurities are added. Fourth, fluid flow models involve processes on very different time scales, such as pressure waves, boiling and condensation, and mass transport, which make compromises between computational accuracy and efficiency necessary.

At the beginning of the project, a literature study of models and simulation tools for pipeline transport was performed. The study highlighted running ductile fractures as an important area of research, since such fractures present one of the main risks of CO_2 pipeline transport. These fractures propagate due to the high pressure inside the pipe, so accurate prediction of the speed of pressure waves is necessary. There are many assumptions necessary when modelling this process, each with their own characteristic pressure wave speed. This is illustrated in Figure 20, which shows the decompression velocity for different models and chemical components. A lower curve means a lower risk of running fractures. Experimental data for this speed are scarce, but would be highly useful to validate models for running fractures.

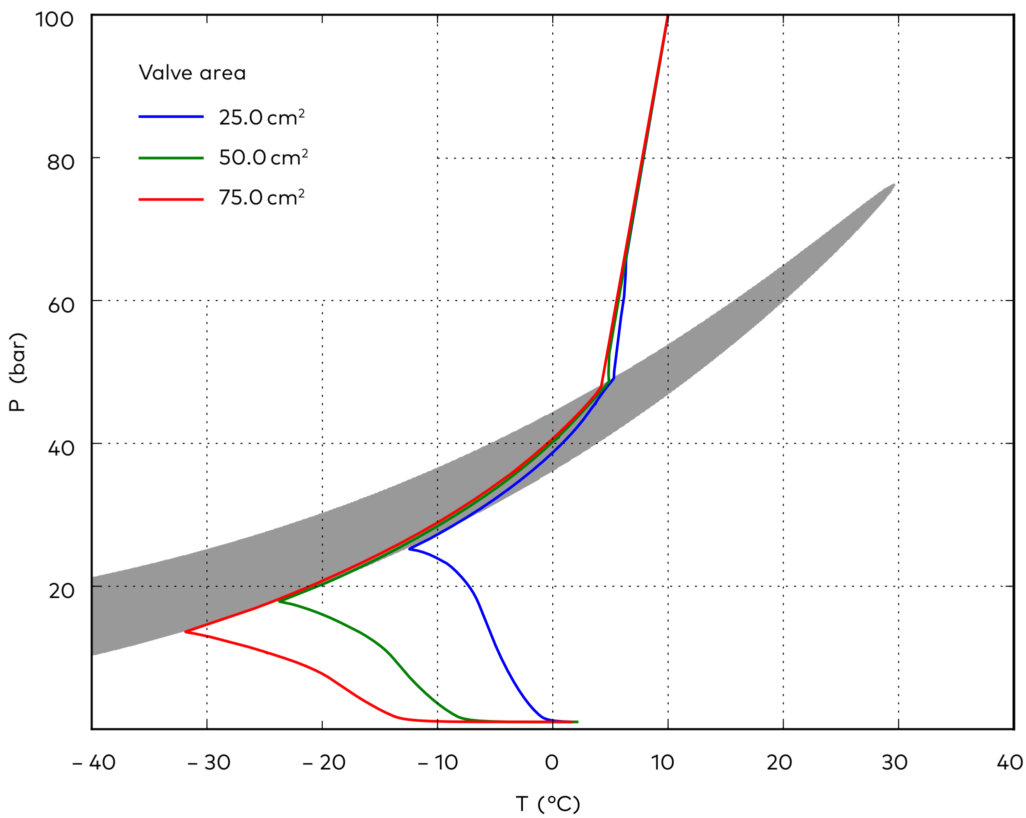


Figure 21. Temperature during depressurization of a pipeline with 98% CO_2 and 2% N_2 for different valve openings. The shaded area is where both liquid and gas are present.

CO_2 streams from capture processes contain mostly CO_2, but also some impurities. The level of impurities can have a large impact on how pipelines should be operated. Two effects of impurities are especially relevant for pipeline flow: where the boiling point of the liquid is, and how low temperatures can be expected during emptying of a pipe. Low temperatures can be damaging to the pipe steel and other equipment, and should therefore be predicted accurately. In Task 5.2, we investigated how volatile impurities like nitrogen, oxygen, hydrogen, methane and hydrogen sulphide affected the boiling temperature. The study concluded that small amounts of nitrogen and oxygen increase the boiling temperature significantly, which should be taken into account when operating a pipeline with large amounts of nitrogen and oxygen in the CO_2 stream. The area of the valve through which the pipe is emptied, in other words how quickly the pipe is emptied, can have an even stronger impact on the temperatures, as shown in Figure 21.

Many simulation tools for oil and gas flow exist, but few support flow of CO_2 or CO_2 mixtures with sufficient accuracy and robustness. Since CO_2 has significantly different properties from oil and natural gas, special models are needed. In Task 5.2, two existing tools that handle pure CO_2, OLGA and the SINTEF Energy Research in-house code were compared. The differences in results from the two codes could partially be attributed to different numerical algorithms, but model differences can also play a significant role. It is therefore crucial to be aware of the modelling assumptions and limitations of the chosen simulation tool when interpreting simulation results.

3.5.3 Industry Benefits

Better knowledge of uncertainties in CO_2 flow modelling and the effect of impurities can improve pipeline design and give better recommendations for acceptable impurity levels. The techno-economic analysis shows that ship transport is the least costly transport option for most of the sources individually as well as for most of the potential clusters during ramp-up. Hence, there will be no need to build costly, large-scale pipelines until such volumes have been reached that pipeline is a cost efficient transport solution.

3.6 CO_2 Storage (WP 6)

The CarbFix project. Edda Sif Aradóttir stores CO_2 in porous basaltic lava. Testing facilities outside Reykjavik. Photo: NordForsk/Terje Heiestad


Edda Sif Aradóttir

3.6 CO_2 Storage (WP 6)

3.6.1 Highlights

An important part of the project has been to generate an atlas that ranks potential CO_2 storage sites (https://data.geus.dk/nordiccs/map.xhtml), and the conclusion is that the Nordic region has substantial storage capacity in aquifers. The atlas identifies 20 suitable Nordic sites, with the most promising sites located in Norway.

The web-based Nordic CO_2 Storage Atlas was published in November 2015. It comprises an extensive storage site database based on geological data from the Nordic region. The atlas can be used as basis for planning future CCS infrastructure and to support decisions on how the Nordic countries can manage their CO_2 reduction targets towards a carbon neutral Nordic region in 2050.

In order to create this storage atlas, an extensive collection of geological data for potential storage sites are merged in a GIS (Geographic Information System) database. The database contains outline and location of sedimentary basins, storage formations, storage units, storage traps, hydrocarbon fields, and mineral trapping storage areas.

Interpretations of seismic surveys and exploration well logs have made it possible to map approximate outlines of reservoirs. In order to illustrate reservoir integrity and complexity, mapping of caprock (seal) formations were included, together with the fault system and exploration well locations. The GIS-database has furthermore been supplemented with information about large CO_2 emitters in the region. A ranking procedure, based on the collected data for reservoirs and seals, has resulted in a selection of the most prospective Nordic storage sites. The characterization and ranking of storage sites was based on four main categories: reservoir properties, seal properties, safety/risk, and maturity/data coverage (Anthonsen et al. 2014).

One task of the NORDICCS storage group was to compare static storage capacity estimates with estimates based on dynamic simulation. One of the main conclusions of this CO_2 injection simulation was that the total storage capacity from static calculations was reduced in relation to the modelled dynamic calculations. However, even when taking a reduction of static capacity estimates into account, it is obvious that the Nordic region has substantial storage capacity in saline aquifers.

3.6.2 Description of Activities

The Nordic CO_2 Storage Atlas (Task 6.1)

The newly released Nordic CO_2 Storage Atlas combines data from previous CO_2 storage screening and mapping projects (GESTCO, EU GeoCapacity and the Norwegian CO_2 Storage Atlas) with new data for areas not previously covered. The atlas gives an overview of storage options and associated reservoir properties for Denmark, Norway, Sweden and Iceland.

Large-scale geological storage of CO_2 depends on the presence of a porous (the space between mineral grains) and permeable (the connectivity between the pores) subsurface layer (aquifers) with an adequate top seal. Areas with the largest storage potential are associated with sedimentary basins containing widespread sandstone layers. Sedimentary basins with storage potential are situated as a belt around the Scandinavian Peninsula from the Baltic Sea, through Denmark and along the Norwegian coast, whereas the shallow sedimentary basins in Finland are not considered appropriate for CO_2 storage (Figure 22). The Storage Atlas also contains data for the Danish and Norwegian hydrocarbon fields. In general, the storage capacity associated with hydrocarbon fields is minor compared to storage in saline aquifers, but late stage production may gain from CO_2 injection improving the production of oil (EOR, Enhanced Oil Recovery). In Iceland, the storage potential is not related to sedimentary basins, but to chemical bonding in porous basalts.

The compiled data were used for characterization and ranking of storage areas. The ranking criteria were grouped into four main categories: reservoir properties, seal properties, safety/risk, and maturity/data coverage and resulted in selection of the most prospective Nordic storage areas based on available geological knowledge up to 2014 (Anthonsen et al. 2014) (Figure 22).

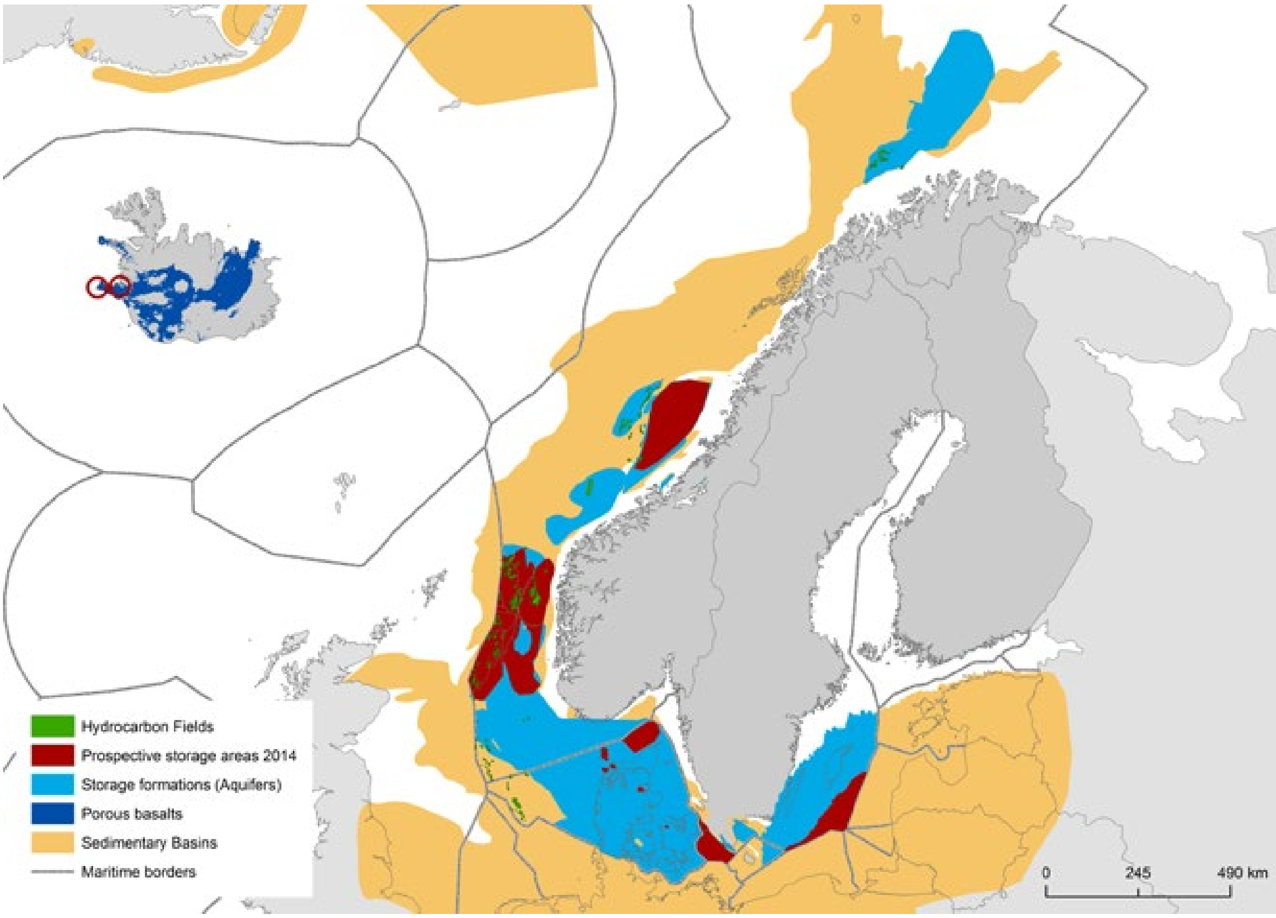


Figure 22. The mapped Nordic storage formations (aquifers) in blue and the selected most prospective areas in red. The dark blue areas on Iceland are the high porous basalt areas and the red circles shows the most promising areas for injection of CO_2.

The total mapped storage CO_2 capacity for Denmark, Norway and Sweden is approximately 134,000 Mt. The storage capacity related to saline aquifers is 120,000 Mt, with 22,000 Mt in Denmark, 94,600 Mt in Norway (72,800 Mt in the North Sea) and 3,400 Mt in Sweden. The total number includes 14,000 Mt in hydrocarbon fields, with 2,000 Mt in Denmark and 12,000 Mt in Norway. It should be emphasized that the storage capacities are regarded as qualified theoretical estimations based on volumetric calculations of the available pore space and a storage efficiency factor. Improved geological data and reservoir modelling work will be needed to narrow the uncertainties for the storage capacity estimate. Storage capacity for porous basalts is based on a different methodology and for onshore Iceland, the calculated capacity ranges between 21,000 and 400,000 Mt depending on the calculation approach.

Storage sites Units (U), Traps (T)	Country	Knowledge gaps (min score -78)	Theoretical Capacity (Gt)
Frigg Fm. (U)	Norway	-17	1.2
Utsira Fm. (U)	Norway	-22	21.3
Johansen Fm. (U)	Norway	-26	0.8
Sognefjord Fm. (U)	Norway	-28	11.5
Garn Fm. (U)	Norway	-43	8.0
Havnsø (T)	Denmark	-47	0.9
Gassum Aq. (U)	Denmark/Norway	-48	3.7
Gassum (T)	Denmark	-49	0.6
Thisted (T)	Denmark	-57	11.0
Faludden (U)	Sweden	-60	0.7
Hanstholm (T)	Denmark	-62	2.8
Arnager Greensand (U)	Sweden	-64	0.5
Höganäs-Rya (U)	Sweden	-76	0.5

Table 3. Evaluation of knowledge gaps for 5 Danish, 5 Norwegian and 3 Swedish top ranked storage sites. Minimum score is -78 and represents no knowledge, highest score is 0. Theoretical storage capacity is listed for each site.

Guidelines for safe storage in the Nordic region (Task 6.2)
As part of the project, available data on storage resources in the Nordic countries has been reviewed and mapped. The mapped storage aquifers, units and traps have been screened and ranked based on maturity, data quality and a set of geoscientific-based criteria evaluating the reservoir and sealing properties. The ranking resulted in top score for several of the evaluated storage sites but there is still a large uncertainty in many of the evaluated parameters and more data and knowledge is required before any of the sites are ready for CO_2 injection.

From the ranking of potential Swedish, Danish and Norwegian storage units and structures, 18 storage sites (10 Norwegian, 5 Danish and 3 Swedish) have been selected as the best potential CO_2 storage options in deep saline aquifers. The total estimated theoretical storage capacity for the top ranked sites is around 86 Gt, which should be sufficient to store the equivalent cumulative mass of the current annual CO_2 emissions from Nordic industry sources over more than 500 years. Including all storage options in saline aquifers in the Nordic countries would increase the capacity beyond this level and further open the possibility for significant storage of CO_2 from European sources.

CO_2 for EOR could increase the ultimate recovery for many of the water-flooded oil fields in Denmark and Norway and introduces an added value for the CO_2. Thus, from an economic point of view, CO_2 storage related to EOR has the highest potential to initiate industrial-scale CO_2 storage. The knowledge gaps related to producing oil fields are also smaller than for aquifer storage sites.

To provide guidelines for advancing the readiness level for CO_2 storage in the Nordic region, remaining knowledge gaps have been identified among the top ranked storage sites. Remaining steps required for characterisation and assessment of the selected storage resources have been identified and gives an indication of where it would be wise to focus the work to advance CO_2 storage in the Nordic countries. Table 3 gives the main results of the knowledge gap analysis. To advance the readiness level of CO_2 storage in the Nordic region, the identified knowledge gaps for the top ranked aquifers should be reduced, e.g. by data collection and realistic dynamic modelling including risk assessment.

Knowledge from CO_2 injection operations are valuable and can drive the technology further. Therefore, the best approach for advancing the knowledge of CO_2 storage in the Nordic countries, a pilot storage operation and/or EOR with aquifer storage using Nordic CO_2 sources should be the prioritized research target.

CO_2 for EOR could increase the ultimate recovery for many of the water flooded oil fields in Denmark and Norway and introduces an added value for the CO_2. Thus, from an economic point of view CO_2 storage related to EOR has the highest potential to start industrial scale CO_2 storage. The knowledge gaps for producing oil fields are also smaller than for aquifer storage sites.

Details of the available storage resources, EOR opportunities, the ranking procedure and the knowledge gap analysis are reported in the open NORDICCS deliverables D6.2.1201, and D6.2.1302.

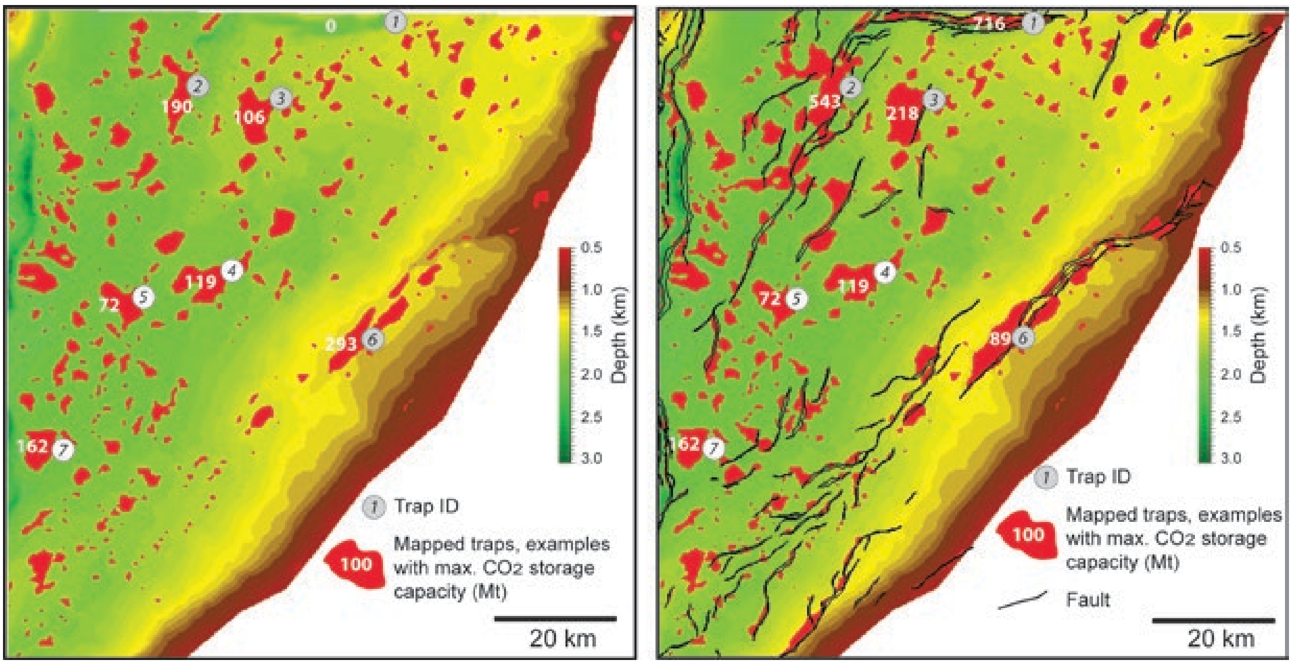


Figure 23. Simulated storage capacity using basin modelling approach for the Trøndelag Platform area estimating left map: open faults and right map: sealing faults. Red color show mapped traps with CO_2 storage capacity in Mt. From Lothe et al. (2016).

Safe storage modelling (Task 6.3)
In order to quantify the CO_2 storage capacity and volumes, modelling were performed using basin modelling and reservoir modelling approach. Dynamic capacity estimates have been carried out for the Gassum Formation in Norway and Denmark, the Garn Formation and the Trøndelag Platform (Norway), the Faludden sandstone in southeast Baltic Sea (Sweden) and the Arnager Greensand Formation in southwest Scania (Sweden).

The open dipping Gassum Formation has an estimated storage capacity of 3.7 Gt CO_2 for the northeastern part of the Skagerrak area (Bergmo et al. 2013). This represents a storage efficiency of 2.0 %, including dissolved CO_2 in the formation water. Dynamic models for the Hanstholm structure, offshore Denmark give a storage capacity of approximately 1.17 Gt. The capacity for the Vedsted structure is about 0.125 Gt.

The Garn Formation on the Trøndelag Platform offshore Central Norway has in the structural closures a storage capacity of approximately 2.0 Gt to 5.2 Gt, assuming no migration loss and a very low dissolution rate in the traps (Figure 23). Taking into account all results, the estimated representative storage capacity is ranging between 2.0 and 3.5 Gt (Lothe et al. 2016). Scanning of safe injection sites revealed several locations where CO_2 with a rate of one Mtpa could be injected without migrating out of the working area. These sites were verified using different modelling approaches.

In the case of the Faludden sandstone, the different modelled scenarios give a spread from 10 to 836 Mt and a representative capacity of 250 to 435 Mt was defined (Lothe et al. 2016). For the Arnager Greensand Formation at least 26 Mt CO_2 can be stored in traps whereby the storage capacity below 800 m is reduced to only 10 Mt. The dynamic migration modelling suggests that ca. 225 Mt CO_2 can be injected whereby only 3.3 % would migrate to depths less than 800 m.

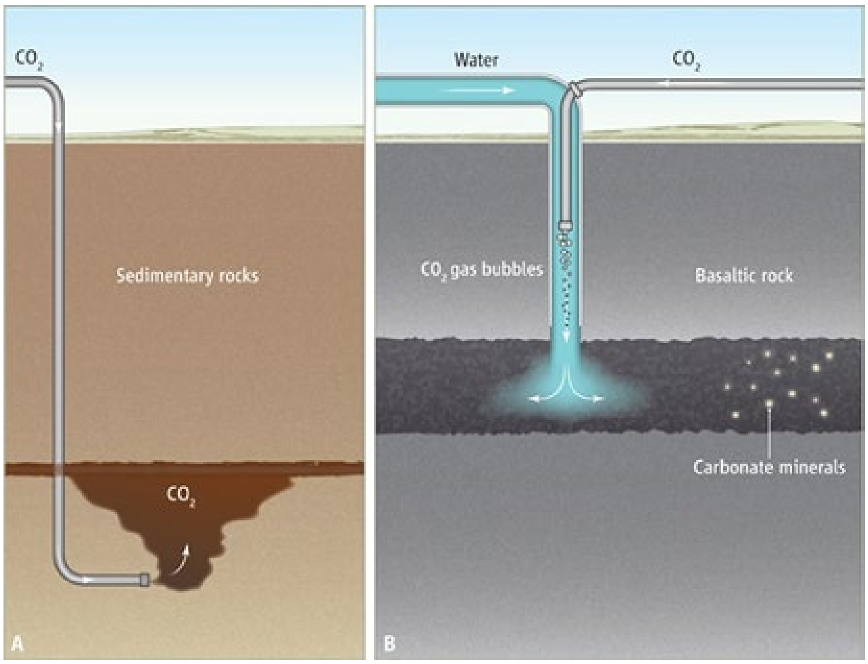


Figure 24. Carbon storage in sedimentary basins and basaltic rocks. (A) Carbon storage in sedimentary basins; CO_2 is injected as a separate buoyant phase and is trapped below an impermeable cap rock. (B) In the CarbFix method, CO_2 is dissolved into water during injection into porous basaltic rocks. No cap rock is required because the dissolved CO_2 is not buoyant and does not migrate back to the surface. Figure from Gislason and Oelkers, 2014.

CO_2 injection in basalts

In most carbon storage projects to date, CO_2 has been injected as a buoyant supercritical phase into sedimentary basins where it is anticipated that the CO_2 is trapped below an impermeable cap-rock. In Iceland an alternative method is being developed and tested as a part of the CarbFix project (www.carbfix.com) where the CO_2 is dissolved into water during injection into basaltic rock formations (Gislason and Oelkers, 2014) (Figure 24). Once dissolved in water, the CO_2 is no longer buoyant and does not migrate back to the surface. Basaltic rocks are reactive and contain over 25 wt% Ca, Mg and Fe-oxides. The CO_2-charged water accelerates both the metal release from the basalt and subsequent formation of solid carbonate minerals such as Calcite ($CaCO_3$), Dolomite ($CaMg(CO_3)_2$), Magnesite ($MgCO_3$), siderite ($FeCO_3$), and solid solutions thereof, for long term storage of CO_2.

A vast amount of water is required to dissolve the CO_2, depending mostly on pressure, temperature, and salinity (Gislason et al., 2010). At 25 bar CO_2 pressure and 25°C, about 27 t of pure water is required for dissolving each tonne of CO_2, and at 25 bar CO_2 pressure and about 4°C about 20 t of seawater of average 35‰ salinity is required per tonne CO_2.

Basalt is the dominant rock type on Earth's surface, covering most of the oceanic floor and about 5% of the continents (Dessert et al., 2003; Wilson, 1989). The offshore formations offer a unique environment for CO_2 storage with a vast volume of pore space, and fresh and reactive rocks adjacent to nearly unlimited supplies of seawater. The oceanic ridges extend through all of the major ocean basins, with a total length in excess of 60,000 km (Wilson, 1989). The theoretical integrated CO_2 storage capacity of the ridge system has been estimated to be of the order of 100,000-250,000 Gt CO_2 (Snæbjörnsdóttir et al., 2014) considerably larger than the estimated CO_2 emission from burning all fossil fuels on Earth (Archer, 2005).

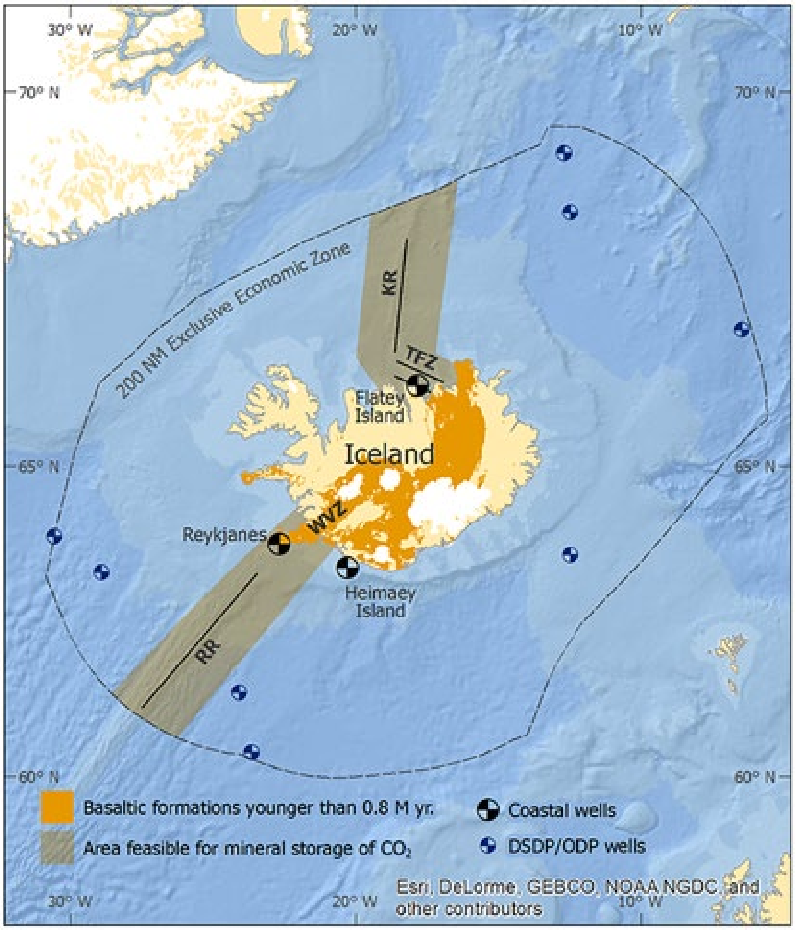


Figure 25. General outlines of the plate boundary in Iceland. Reykjanes Ridge (RR) enters Iceland at the tip of the Reykjanes Peninsula which extends to form the Western Volcanic Zone (WVZ). The Northern Volcanic Zone (NVZ) extends north where it is linked to the offshore Kolbeinsey Ridge (KR) by the NW-trending Tjörnes Fracture Zone (TFZ). Large hourglass circles indicate wells drilled in the coastal areas and small hourglass circles indicate wells drilled offshore as a part of DSDP and ODP. Figure from Snæbjörnsdóttir and Gislason, 2015.

Iceland is the largest landmass above sea level at the oceanic ridges. Iceland's area is 103,000 km^2 and mostly made of fresh basaltic rocks, which makes it an ideal location for conducting experiments on mineral storage in basalts, such as done in the CarbFix project. Two injection experiments were conducted in Hellisheiði, SW-Iceland in 2012 where 175 t of pure CO_2 were injected from January to March 2012 and 73 t of a 75% CO_2/24% H_2S/1% H_2 gas mixture from the Hellisheiði Geothermal Plant in June-August 2012. More than 80% of CO_2 injected was carbonated within a year at 20°-50°C and 500-800 m depth (Gislason and Oelkers 2014). This result suggests that the CarbFix method can change the time scale of mineral carbon trapping considerably. The experiment was scaled up in April 2014, including capture from the power plant, transport and storage, injecting about 8,500 t of CO_2/H_2S (60%/40%) gas mixture annually.

The feasibility of using seawater for carbon storage in basalts has been tested by experiments in the laboratory. Glassy and crystalline basalts exhibit similar dissolution rates in solutions of varying ionic strength and cation concentration. The rates are accelerated by increasing the CO_2 pressure in seawater, suggesting seawater to be an excellent medium for CO_2 storage in basalt (Wolff-Boenisch et al. 2011; Wolff-Boenisch & Gislason 2012).

The most feasible areas for CO_2 storage on- and offshore Iceland are the youngest formations within the active rift zone, which consist of highly porous and permeable basaltic lavas and hyaloclastic (glassy) formations (Figure 25). These formations are younger than 0.8 million years, from upper Pleistocene and Holocene, and cover about 34,000 km^2 onshore, which is about one third of Iceland and about 93,000 km^2 offshore within the Iceland Economic Zone (Figure 25). It is estimated that this area could store up to 9,000 Gt CO_2 (Snæbjörnsdóttir & Gislason 2015; Snæbjörnsdóttir et al. 2014). Site specific geological research and pilot studies are required for refining the concept and offshore pilot scale projects should be considered as the next steps in evolving the method and revealing how much of this storage potential will be practical to use.

3.6.3 Industry Benefits

The Nordic CO_2 Storage Atlas can be used as basis for planning future CCS infrastructure and to support decisions on how the Nordic countries can manage their CO_2 reduction targets towards a carbon neutral Nordic region in 2050.

Quantification of CO_2 storage capacity and volumes have been verified by modelling using basin and reservoir modelling approaches, reducing the uncertainties and making the storage capacities more reliable.

Guidelines for advancing the readiness level for CO_2 storage in the Nordic region have been identified among the top ranked storage sites and give an indication of where it would be wise to focus the work to advance CO_2 storage in the Nordic countries.

From an economic point of view, CO_2 storage related to EOR has the highest potential to start industrial scale CO_2 storage. The knowledge gaps for producing oil fields are smaller than for aquifer storage sites, and for many of the water-flooded oil fields in Denmark and Norway, EOR can increase the ultimate recovery and give added value for the CO_2.

In Iceland, an alternative method is being developed and tested as a part of the CarbFix project where the CO_2 is dissolved into water during injection into basaltic rock formations. This methodology might in the future prove to be an option for large-scale permanent storage of CO_2.

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3.7 Management and Administration (WP 0)

Lab at SINTEF, from left: Snorre Foss Westman, Ingeborg Treu Røe, Bjørn Holst Pettersen, Nils A. Røkke. Photo: NordForsk/Terje Heiestad

3.7 Management and Administration (WP 0)

The objective of the Management and administration activity (WP 0) has been to facilitate NORDICCS operations. Below is a brief summary of the most important undertakings of the work package.

3.7.1 Highlights

The NORDICCS Summer School was organized twice – in 2013 and 2015. The one-week intensive CCS courses, which gathered 30 participants both times, was held mainly with NORDICCS partners as lecturers, but also external experts contributed. Participants were recruited at the PhD level from universities and industry companies. Both events were financed with external funding. The Summer School was officially acknowledged by NTNU, giving the students three credit hours. The Summer School organizer was Marit Mazzetti (WP 1).

A series of workshops and seminars were staged. Events focused on technical, economical, legal and policy issues. A significant number of external participants, as well as NORDICCS partners attended the events. A listing of the different events can be found in Chapter 4.4.

The NORDICCS Consortium Days were organized annually. Including the Kick-off meeting (2011) and the Final Conference (2015), five events were staged. Typically, these consortium days focused on status of results and plans for the next period. The meetings were held in all Nordic countries, and they were open to external participants.

A total of 15 Steering Group (SG) meetings were held and all Nordic countries have been visited. Nine of the meetings were held as telephone conferences. The Centre Management Group (CMG) consisting of the Centre Management Team (CMT) from the Host Institution and the Work Package Leaders, had 36 meetings – most of them held as telephone conferences. The CMG has in an effective way followed up decisions made by the SG and ensured continuity in operations.

A website for NORDICCS was set up where news, results and events have been announced. The web has been open to external readers throughout the project. With a few exceptions, most deliverables for the NORDICCS project can be found on the web.

Eight high quality NORDICCS Newsletters were produced. The Newsletters have been disseminated each time to approximately 250 recipients, the majority external to the NORDICCS project. Each issue of the Newsletters has included a feature article. The activity was organized by Camilla Mörn, IVL (WP 0).

A significant effort was undertaken in 2012 and 2013 to acquire new members to the NORDICCS consortium. A promotional brochure was produced, and contact was made with between 15 and 20 companies. Meetings were held with a handful companies. Two new members came on board after the start-up of the project, Technology Centre Mongstad and Vattenfall.

Annual working plans (AWPs) were produced for all work packages for each year of the project. The plans have specified deliverables, deadlines and budgets. To the extent deviations have occurred, deviation requests were submitted to the CMT for formal approval.

The CMT, together with the Work Package Leaders, has produced and annual administrative reports for submission to Nordic Innovation. Altogether five reports (including this Final Report) were produced.

Throughout the duration of the NORDICCS project, the intention has been to continue the cooperation after 2015, possibly with even more participants. In 2014, the Steering Group organized a separate Strategy Day (August 25) on this topic in connection with the Consortium Day in Iceland. This meeting marked the beginning of the development of a new application and a strategy for continued operation of NORDICCS.

3.7.2 Industry Benefits

The NORDICCS project has contributed significantly in building of capacity and networks. These are benefits expected to have long-lasting effects.

In terms of capacity building, especially the two NORDICCS Summer Schools are important contribution. More than 60 young researchers PhDs and Post Docs from Nordic universities and industry companies attended and completed these one-week intensive CCS courses. Lectures were given by the most prominent Nordic CCS experts, offering the students state-of-the art knowledge. The students were given highly relevant exercises, such as the mandatory exams. Results from the exams were used as input to the NORDICCS Roadmap. Most of the Summer School students will eventually find jobs in industry companies, where their increased knowledge will benefit the Nordic CCS industry.

The networking effects of the NORDICCS project have proven very valuable. The CCS challenges in the various Nordic countries are different. CO_2 storage capacity, for instance, is abundant in Norway but not available in Finland. Bio-energy is far more widespread in Sweden than in any of the other countries, so bioCCS could be of importance to Sweden. All this means that by combining challenges, competence and possibilities in the different countries, possibilities are for establishing complete and optimal CCS value chains in the Nordic region. This will have positive bearings for the Nordic industries when the CCS market is developed.

Cooperation in projects such as NORDICCS also represents an effective pooling of resources. Instead of funding similar projects in two or more countries, larger projects where all countries participate yields a situation where funds are not spent several times for the same purpose. To the extent the industry contributes funding, industry will achieve higher return on their money spent.

Without exception, the NORDICCS partners have experienced the project as very positive. They are eager to continue the cooperation and a new concept for prolongation is already developed. Unfortunately, not enough funding is yet secured. However, efforts will continue, and the aim is to have a second phase of the project established within 2016.

[4] Communication and Dissemination of Results

Participants at the Nordic CCS Summer School in 2015. Photo: Chameera Jayarathua

4.1 Communication plan

One of the early activities in NORDICCS was the development of a communication plan (2012). This plan gave directions on the most important communications channels and activities. The plan has been updated and refined. The most important channels of communication have been; the website, the newsletter, meetings/events organized by NORDICCS, journals, conferences, and the Nordic CCS Summer School.

4.2 Web

A website was set up at the beginning of the project. The web has the following main sections: About NORDICCS, Motivation, Work packages, Partners, News, Results, Activities and events, Contacts, and Links. The aim of the web has been both project internal and external communication. The web can be found here: sintef.no/projectweb/nordiccs/

4.3 Newsletter

Nine Newsletters were produced during the course of NORDICCS, and have been distributed to around 250 recipients.

2012 No. 1
2013 No. 1, No. 2, No. 3
2014 No. 1, No. 2
2015 No. 1, No. 2, No. 3

4.4 Organisation of Conferences, Seminars, Workshops, etc.

A Consortium Day was held each year during the course of the project. The main intention with the consortium days was to disseminate the latest results and discuss findings of the ongoing activities. These events have been open to the external partners and the public. The following consortium days were staged:

Consortium Day 2011 (Kick-off meeting).
Trondheim, Norway, 2011-11-02

Consortium Day 2012.
Gothenburgh, Sweden, 2012-12-05

Consortium Day 2013.
Copenhagen, Denmark, 2013-11-14

Consortium Day 2014.
Stockholm, Sweden, 2014-11-20

Consortium Day 2015 (Final Conference).
Oslo, Norway, 2015-11-10

A series of seminars and workshops were held with the aim of disseminating results from the project. The most important ones are listed on the next pages.

Barriers and New Strategy for CCS innovation and Implementation. From the panel discussion. Photo: Mette Kjelstad, SINTEF

Carbon Capture and Storage (CCS) R&D in the Nordic countries. Mr. Juho Lipponen speaking at the seminar. Photo: SINTEF

2012-04-17: Barriers and New Strategy for CCS innovation and Implementation.
The seminar was a side-event to Technoport 2012, in Trondheim, Norway. The purpose was to present the plans for the NORDICCS Roadmap and to get input to the development. Approximately 80 persons attended. Member of Parliament Mr. Nikolai Astrup (Høyre, Norway) and Mr. Frederic Hauge of Bellona attended the panel discussion.

2013-10-21: Carbon Capture and Storage (CCS) R&D in the Nordic countries.
The seminar held at Hanasaari, Finland, was co-arranged between the Finish CCSP project (cleen.fi/en/ccsp) and NORDICCS. It aimed at establishing information exchange between the two projects and possibly generating more concrete cooperation. Attendance reached almost 50, mainly from the two projects. Mr. Juho Lipponen of the International Energy Agency (IEA) gave a presentation on IEA's work on the 2013 Nordic CCS Roadmap.

2013-10-22: CCSP and NORDICCS Researcher Workshop
This workshop (Hanasaari, Finland) investigated concrete possibilities for cooperation between the two projects. Technical issues in both projects were discussed. The meeting was attended by representatives of the BASTOR and the BASREC projects.

2013-11-28: NORDICCS Seminar in at the Nordic Council of Ministers 65th Session
This seminar was held at the Norwegian Parliament (Stortinget) in conjunction with the 65th session of the Nordic Council of Ministers (NCM). 30 attendees were given presentations about the NORDICCS activities. A highlight of the seminar was the panel discussion, which was attended by Ms. Cecilie Tenfjord-Toftby of Sweden, Chair of the Nordic Council Business and Industry Committee of the NCM and Ms. Christina Gestrin, Vice-Chair of the Nordic Council Environment and Natural Resources Committee, NCM.

Meeting with the UN Climate Envoy. From left: Gunnar Bovim (Rector, NTNU), Torstein Haarberg (SINTEF), Jens Stoltenberg (UN Special Envoy on Climate Change), Gabriella Tranell (NTNU), Edgar Hertwich (NTNU) and Nils A Røkke (SINTEF). Photo: Petter Haugan, SINTEF

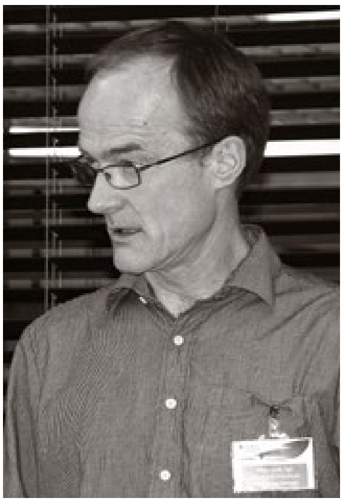
The International Carbon Conference: President of Iceland, Dr. Olafur Ragnar Grimsson and NORDICCS Director Dr. Nils A. Røkke. Photo: SINTEF

2014-02-04: Meeting with the UN Climate Envoy
Leader of NORDICCS met with the UN Special Envoys on Climate Change, former Prime Minister Jens Stoltenberg. Mr. Stoltenberg visited SINTEF and NTNU seeking advice on climate issues. During his CCS presentation for Stoltenberg, Dr. Røkke wore his NORDICCS hat, explaining how this work has resulted in a roadmap for CCS in the Nordic countries and how this knowledge and method can be used for a global CCS roadmap.

2014-08-26/27: The International Carbon Conference
The conference was jointly organized by the projects: CarbFix, CO_2-React, MetTrans, MINSC and NORDICCS in Reykjavik, Iceland. With the aim of informing the audience on some of the most important ongoing CCS projects, the conference drew over 100 participants. All presentations were invited, and NORDICCS had three contributions. The Conference was opened by a very interested and enthusiastic President of Iceland, Dr. Olafur Ragnar Grimsson.

2014-10-28: Joint NORDICCS and CCSP Seminar
This was the second time the two projects joined forces in a seminar to share experiences and to investigate possibilities for joint efforts. Deputy Director General at the Ministry of Petroleum and Energy, Mr. Egil Meisingseth, presented the Norwegian Government's position on CCS, and Hans Jörg Fell, Leader CLIMIT secretariat, presented possibilities for the two projects for activities under the CLIMIT program. Around 40 attendees joined the seminar.

2014-10-28: Workshop on Legal Issues in CCS
The workshop elucidated the legal and business issues that will arise related to shipping and transport of CO_2 for the purpose of EOR/offshore storage in the Nordic/Northern European region. It gave recommendations for further actions necessary in order to pave the way for CCS as well as new business opportunities in the area. Around 35 participants attended the workshop, and presentations were given from Statoil, DNV-GL, and Arntzen de Besche.



Joint NORDICCS and CCSP Seminar. Egil Meisingseth, Ministry of Petroleum and Energy, presents Norway's position on CCS. Photo: SINTEF

Workshop on Legal Issues in CCS. Ingvil Ombudstvedt of Arntzen de Besche during presentation on CCS legal issues. Photo: SINTEF

CCS in the Nordic Region. Dr. Johnny Fredericia, CEO of GEUS welcoming participants to the seminar. Photo: SINTEF

NORDICCS Final Conference. Svein Søyland, Nordic Energy Research. Photo: SINTEF

2014-11-19: Workshop Stockholm
The day before the NORDICCS Consortium Day in Stockholm, a workshop was organized to display the NORDICCS activities to a broader Swedish audience. The topic for the workshop was the zero emission strategy in a Nordic industry perspective and what role the CCS technology has and should play. External experts from Sweden represented: SSAB, Cementa and Chalmers University. Around 50 experts attended.

2015-04-23: Seminar "CCS in the Nordic Region"
The seminar focused on the latest developments within CCS and on possibilities for implement CCS technology in the Nordic region. Some of the issues raised were: business opportunities, involvement of politicians, and potential economic models for CCS. The seminar took place in Copenhagen with around 30 participants.

2015-11-10: NORDICCS Final Conference.
The Final Conference held in Oslo, Norway, marked the end of the NORDICCS project, and the aim was therefore to present the overall and final results. More than 40 participants attended, and almost half of them were external to the project. As a representative from the funding organizations, Mr. Svein Søyland, Nordic Energy Research, gave a presentation on the Green Growth Project, which could be a possibility for funding continued operation of NORDICCS. Several of the external participants expressed great satisfaction with the outcome of NORDICCS and disappointment with the fact that no funding has yet been found for a continuation.

Participants at the first Nordic CCS Summer School in August 18-23, 2013. Photo: Chameera Jayarathua

4.5 Publications

Publication of results from activities was given high priority in NORDICCS. Altogether 113 publications were produced. The list of publication can be found in the Statistics chapter (p. 94). The numbers of publications in the different categories are as follow:

- Conference presentations (oral): 50
- Journal publications (peer reviewed): 23
- Poster presentations: 16
- Reports/thesis: 10
- Popular science articles: 6
- Policy briefs: 3
- Information material: 2
- Newspaper chronicle: 2
- Book chapter: 1

NORDICCS representatives have participated at a significant number of high-profile conferences to promote project results. Even at the two most prestigious conferences, the International Conference on Greenhouse Gas Technologies (the GHGT series), and the Trondheim Conference on CO_2 Capture, Transport and Storage, NORDICCS representatives have been very visible. The combined number of contributions at the two last GHGT conferences is nine, and at the two last TCCS conference the number is 17.

4.6 Summer School

The Nordic Summer School was organized twice – in 2013 and 2015. This was a one-week intensive CCS course where students were given state-of-the art information. Prime candidates for attending were PhD candidates and young researchers in the field of CCS. A requirement was that the participants had to study or work with CCS at a Nordic university or a company with foothold in a Nordic country.

The Summer School turned out to be a very popular event between the participants. Both times the 30 available openings were filled, and several candidates were turned down. Primarily the lecturers were selected from the NORDICCS partners, but also external lecturers were used. Additional funding to the Summer School came from the Research Council of Norway, the CLIMIT program and Gassnova.

4.7 Top-level Research Initiative (TRI)

TRI book: In November 2015 the book "Solving the Climate Crises" was released which presents some of the important results that have been obtained through the TRI initiative and features interviews with decision-makers and researchers, including the NORDICCS project.

To download the book please go to
toppforskningsinitiativet.org/en/om-toppforskningsinitiativet/book

TRI film: For a video presentation of the TRI and a selection of the results please go to:
toppforskningsinitiativet.org/en/om-toppforskningsinitiativet/video

Information about other projects funded within the TRI:
toppforskningsinitiativet.org/en

[5] Recommendations for Further Activities

Technology Centre Mongstad (TCM) in Norway. Photo: TCM


CO2 TECHNOLOGY CENTRE MONGSTAD

[5] Recommendations for Further Activities

The NORDICCS project has generated new and useful knowledge in many areas. Yet, new challenges have arisen. Based on the findings and experiences from the project, the following are recommendations for further activities.

The NORDICCS project, in one form or another, should continue. The successful outcome of the project as evidenced by feedback from industry, politicians, NGOs, as well the partners, suggests that the Nordic collaboration should continue. The project has generated a Nordic "CCS team" with a common vision, and an enthusiastic spirit. A continued joint collaboration would facilitate a holistic approach to the Nordic challenges and efficient use of resources.

Assumptions and Premises

The outcome of NORDICCS has pinpointed several areas of future work that are relevant for implementation of Nordic CCS projects. In terms of framework conditions, the strategy workshops involving external experts have proved very useful, and should be continued. Also, the *Nordic CCS Roadmap* should be updated in regular intervals, say every two years. Last but not least, the success of the *Nordic CCS Summer School* calls for continuation.

End use of CO_2 should be studied to a greater extent.

Communication

The *political debate* on CCS at the national level should be intensified, particularly in Denmark, Sweden and Finland. It should be discussed seriously what possible role CCS should play in long-term emission cut strategies and what it means for short-term strategies.

The *dialogue between industry and policymakers* should be intensified, in order to move forward with the discussion on the future role of CCS.

Knowledge sharing at the local level should be enabled, to discuss locally / regionally relevant CCS issues. It should be consider setting up a *dialogue platform* in the Skagerrak region, allowing municipalities and other local actors to discuss local concerns and exchange knowledge.

The *design of communication plans towards the public* should be taken seriously and the abundant literature on the topic should be consulted. Review existing toolkits and guidelines before engaging with the local community.

A *genuine dialogue* about CCS with the local community should be established. One should take into account public concerns and ensure a transparent process.

At the national level, it would be relevant to *study policymakers as communication targets*. How does communication towards policymakers occur and what could trigger political interest in CCS? Related to this, it would be valuable to study the preconditions for Nordic collaboration. As there are limited existing policies and political dialogue about transnational CCS solutions, it would be useful to study national policymakers' views before and after discussing concrete cases.

On the local level, the *analysis of municipalities' views on CCS* could be extended to other areas in the Nordic region and include other stakeholders than those covered in NORDICCS. This could also provide knowledge about whether the local community's view on CCS would be affected by new technology developments, e.g. if the CO_2 originates from biomass or if the CO_2 is reused for commercial purposes and included in local business development.

CO_2 Capture

More investigation should be undertaken to reduce the *energy penalty and other costs* in CO_2 capture processes. Through the technical case studies it has been shown that the energy requirement in some of the CO_2 capture technologies assessed is significant. For instance, the regeneration energy required for the amine absorption reboiler is significant. Globally, further research to lower the energy demand for CO_2 capture is ongoing, and the conclusions from NORDICCS justifies that such research continue.

Demonstration projects for CO_2 capture and storage need to be developed, improving readiness for widespread CCS deployment. In particular, integrated projects encompassing the whole CCS chain are needed.

There is a need to *develop CCS chain ownership*, to build up infrastructure and start the first CCS chains. Industries alone cannot provide the development of CCS technologies needed. This means that governments must take the lead, as has been the case in several earlier technology developments. As for now, the cost and uncertainty is too high, and the incentives for developing a CCS chain are too low.

Nordic CCS clusters for CO_2 capture should be established. Such clusters could include waste incinerators, biomass fired plants, cement and steel.

CO_2 Transport

The work of *comparing models and simulation tools* to experimental data should be continued. Different simulation tools and models rely on different assumptions, some of which have not (yet) been justified experimentally. In order to improve reproducibility of simulation results, open information on each detail of the model used is essential. In light of recent research results, the challenges of CO_2 ship transport should be given more attention in the future.

New technologies for ship transport of CO_2 should be studied.

CO_2 Storage

Long-term, safe, reliable, and publicly accepted offshore CO_2 storage is crucial for Nordic CCS deployment. For many potential storage sites, more and better data are needed to understand storage mechanisms, dynamic CO_2 reservoir behaviour as well as suitable monitoring techniques and mitigation measures in the event of CO_2 leakage. More injection pilots should be executed to build knowledge needed for injection well design and optimal location determination. Especially the promising Faludden and Gassum sites should be investigated to reduce uncertainty in injectivity and storage volume. This is true for both ramp-up situations and long-term performance.

New knowledge from CO_2 injection operations would be valuable and should be developed. This can drive the technology further.

A pilot storage operation and/or EOR with aquifer storage using Nordic CO_2 sources should be the prioritized research target in the Nordic countries.

Improved geological data and *reservoir modelling* work will be needed to narrow the uncertainties for the storage capacity estimate.

The identified knowledge gaps for the *top ranked aquifers* should be reduced, e.g. by data collection and realistic dynamic modelling including risk assessment.

For CO_2 injection in basalts, *site-specific geological research and pilot studies* are required for refining the concept and offshore pilot scale projects should be considered as the next steps in evolving the method and revealing how much of this storage potential will be practical to use.

Cost estimations of the most promising Nordic storage concepts should be developed. A joint Nordic CO_2 hub and storage site is essential to implement as per the current Nordic CCS roadmap.

Illustration: Natalia Frenta Lukiyanova/Shutterstock

Main Deliverables

Item	Activity	Due date	Responsible
D1	Annual Convention I – Summary Document	2012-05-14	SINTEF ER
D2	Annual Convention II – Summary Document	2013-05-14	SINTEF ER
D3	Annual Convention III – Summary Document	2014-05-14	SINTEF ER
D4	Annual Convention IV – Summary Document	2015-05-14	SINTEF ER
D7	Strategies for CCS realization	2015-03-14	SINTEF ER
D11	Relevant CCS cases identified	2012-12-14	Tel-Tek
D12	Relevant CCS cases identified – Update	2013-10-14	Tel-Tek
D13	Case synthesis	2013-12-14	Tel-Tek
D14	Case synthesis – Update	2014-10-14	Tel-Tek
D15	Identification and communication of knowledge gaps and industry R&D recommendations	2015-03-14	Tel-Tek
D17	Input to feasibility studies (WP 3)	2013-06-14	VTT
D18	Input to feasibility studies (WP 3) – Update	2014-06-14	VTT
D21	Recommendations on models and modelling tools	2014-06-14	SINTEF ER
D24	Guidelines for CO_2 storage in the Nordic region	2015-03-14	SINTEF PR
D25	Estimation of improved capacity and quantification of capacity and sealing properties	2013-06-14	SINTEF PR
D26	Estimation of improved capacity and quantification of capacity and sealing properties – Update	2014-10-14	SINTEF PR
D27	SG meeting – MOM (1)	2011-08-14	SINTEF ER
D29	Procedures and tools for project follow-up	2011-10-14	SINTEF ER
D30	SG meeting – MOM (1)	2012-06-14	SINTEF ER
D32	SG meeting – MOM (1)	2012-12-14	SINTEF ER
D33	SG meeting – MOM (1)	2013-06-14	SINTEF ER
D35	SG meeting – MOM (1)	2013-12-14	SINTEF ER
D36	SG meeting – MOM (1)	2014-06-14	SINTEF ER
D38	SG meeting – MOM (1)	2014-12-14	SINTEF ER
D39	SG meeting – MOM (1)	2015-06-14	SINTEF ER
D43	Overview of Nordic CCS activities	2012-06-14	IVL
D44	1st Newsletter (2)	2012-06-14	IVL
D45	2nd Newsletter (2)	2013-08-14 (3)	IVL
D46	3rd Newsletter (2)	2014-06-14	IVL
D47	4th Newsletter (2)	2015-06-14	IVL

Main Deliverables, notes:

(1) The contract between Nordic Innovation and SINTEF Energy Research called for eight Steering Group meetings. Altogether, the Steering Group had 15 meetings. Minutes of the all the meetings can be found on the NORDICCS eRoom.

(2) The contract between Nordic Innovation and SINTEF Energy Research called for four issues of the Newsletters. During the course of the project a total of eight newsletters were produced. All eight issues can be found on the NORDICCS website.

(3) The Contract has the due-date 2012-08-14. This is a misprint. The actual date should be as stated in the table above, 2013-08-14

Publications

WP 0

1. Aarlien, R.; Røkke, N.A., *The Nordic CCS Competence Centre Established*, IEA GHG Newsletter, June 2012, Issue 106, Popular science publication

2. Aarlien, R.; Røkke, N.A., *NORDICCS - Nordic CCS Competence Centre: Join us in spearheading CCS deployment in the Nordic Region* (brochure), SINTEF, Mar. 2012, Informational material

3. Røkke, N.A., *The Role of R&D in Enabling CCS - Lessons learnt from NORDICCS and BIGCCS* (Invited presentation), ICC The International Carbon Conference, Reykjavik Iceland, Aug. 26, 2014, Conference contribution (oral presentation)

WP 1

4. Mazzetti, M.J.; Eldrup, N.H.; Anthonsen, K.L.; Haugen, H.A.; Onarheim, K.; Bergmo, P.; Johnsson, F.; Gislason, S. R.; Røkke, N.A., *NORDICCS CCS Roadmap*, Energy Procedia 08/2014; 51:1-13, DOI:10.1016/j.egypro.2014.07.001, July 2014, Journal publication (peer reviewed)

5. Mazzetti, M.J.; Skagestad, R.; Mathisen, A.; Eldrup, N.H., *CO_2 from Natural Gas Sweetening to Kick-Start EOR in the North Sea*, Elsevier, Energy Procedia 12/2014, Nov. 2014, 63:7280-7289, Journal publication (peer reviewed)

6. Mazzetti, M.J.; Skagestad, R.; Mathisen, A.; Eldrup, N.H., *CO_2 from Natural Gas Sweetening to Kick-Start EOR in the North Sea*, International Conference on Greenhouse Gas Technologies (GHGT-12), Austin, USA, Oct. 4, 2014, Conference contribution (oral presentation)

7. Mazzetti, M.J.; Eldrup, N.H.; Anthonsen, K.L.; Haugen, H.A.; Onarheim, K.; Bergmo, P.; Johnsson, F.; Gislason, S. R.; Røkke, N.A., *Nordic CCS Roadmap* (Keynote), The 7th Trondheim CCS Conference - TCCS-7, Norway, June 5, 2013, Conference contribution (oral presentation)

8. Mazzetti, M.J.; Eldrup, N.H.; Anthonsen, K.L.; Haugen, H.A.; Onarheim, K.; Bergmo, P.; Johnsson, F.; Gislason, S. R.; Røkke, N.A., *Nordic CCS Roadmap*, Elsevier, Energy Procedia, June 2013, Journal publication (peer reviewed)

9. Mazzetti, M.J., *CCS-Summer School for researchers and you*, http://blog.sintefenergy.com/nb/?s=summer+-school&submit=S%C3%B8k, 2015, Popular science publication

10. Mazzetti, M.J., *Training Future CCS Experts: Nordic CCS Summer School*, arranged in Norway, http://blog.sintefenergy.com/ccs/training-future-ccs-experts-nordic-ccs-summer-school-arranged-in-norway/, 2015, Popular science publication

11. Mazzetti, M.J., *Nordic CCS Roadmap*, The 8th Trondheim CCS Conference - TCCS-8, Norway, June 17, 2015, Poster

12. Mazzetti, M.J.; Eldrup, N.H.; *Røkke, N.A., Nordic CCS Roadmap Update*, http://www.sintef.no/globalassets/project/nordiccs/nordiccs-roadmap-updated-2015-12-033.pdf, 2015, Report/thesis

13. Mazzetti, M.J.; Eldrup, N.H.; Røkke, N.A., *The Nordic CCS Roadmap*, International Journal of Greenhouse Gas Control, To be submitted 2016, Journal publication (peer reviewed)

14. Mazzetti, M.J., Eldrup, N.H., *Norden kan fjerne CO_2*, Dagens Næringsliv, Feb. 19, 2016, Newspaper chronicle

15. Røkke, N.; Mazzetti, J.M., *CO_2-rensing koster minst på sokkelen*, Teknisk Ukeblad, Norway, Nov. 11, 2013, http://www.tu.no/forskning/2013/11/17/co2-rensing-koster-minst-pa-sokkelen, Popular science publication

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WP 2

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59. Anthonsen, K.L., *NORDICCS - Nordic CCS Competence Centre*, 7th CO2GeoNet Open Forum, Venice, Italy, Apr. 17, 2012, Conference contribution (oral presentation)

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Key Personnel

	Name	Affiliation	Degree	Sex	Position
WP0	Nils A. Røkke	SINTEF	PhD	M	Project Director
	Rune Aarlien	SINTEF	PhD	M	Project Manager
	Jon Magne Johansen	SINTEF	MSc	M	Operations Manager
WP1	Marit Jagtøyen Mazzetti	SINTEF	PhD	F	WP/Task Leader
	Jens Jacob Kielland Haug	SINTEF	MSc	M	Researcher
	Hans Aksel Haugen	Tel-Tek	PhD	M	Department Manager
	Nils Henrik Eldrup	Tel-Tek	MSc	M	Consultant
	Filip Johnsson	Chalmers	PhD	M	Professor
	Klas Andersson	Chalmers	PhD	M	Professor
WP2	Jens Jacob Kielland Haug	SINTEF	MSc	M	WP/Task Leader
	Katarina Buhr	IVL	PhD	F	WP/Task Leader
	Peter Stigson	IVL	PhD	M	WP/Task Leader
WP3	Ragnhild Skagestad	Tel-Tek	MSc	F	Research Scientist
	Anette Mathisen	Tel-Tek	PhD	F	Research Scientist
	Kristin Onarheim	VTT	MSc	F	Research Scientist
	Nils Henrik Eldrup	Tel-Tek	MSc	M	Cost estimatior
	Hans Aksel Haugen	Tel-Tek	MSc	M	Department Manager
WP4	Kristin Onarheim	VTT	MSc	F	Research Scientist
	Antti Arasto	VTT	MSc	M	Bus. Development Manager
	Fredrik Normann	Chalmers	PhD	M	Assistant Professor
	Klas Andersson	Chalmers	PhD	M	Professor
	Stefania Osk Gardarsdottir	Chalmers	MSc	F	PhD candidate
	Sima Ajdari	Chalmers	MSc	F	PhD candidate
	Anette Mathisen	Tel-Tek	PhD	F	Research Scientist
	David Berstad	SINTEF	MSc	M	Research Scientist
	Lars O. Nord	NTNU	PhD	M	Associate Professor
	Amlaku Abie Lakew	NTNU	PhD	M	Researcher
	Kjetil Vinjerui Ekre	NTNU	MSc	M	Researcher

Key Personnel

	Name	Affiliation	Degree	Sex	Position
WP5	Halvor Lund	SINTEF	PhD	M	WP/Task Leader
	Alexandre Morin	SINTEF	PhD	M	WP/Task Leader
	Peder Aursand	SINTEF	PhD	M	Research Scientist
	Morten Hammer	SINTEF	PhD	M	Research Scientist
	Svend Tollak Munkejord	SINTEF	PhD	M	Chief Scientist
	Eskil Aursand	SINTEF	MSc	M	Research Scientist
	Øivind Wilhelmsen	SINTEF	MSc	M	Research Scientist
	Jan Kjärstad	Chalmers	PhD	M	Task Leader
	Ragnhild Skagestad	Tel-Tek	MSc	F	Research Scientist
	Nils-Henrik Eldrup	Tel-Tek	MSc	M	Cost estimator
WP6	Karen Lyng Anthonsen	GEUS	MSc	F	WP/Task Leader
	Ane Lothe	SINTEF	PhD	F	Task Leader
	Gry Møl Mortensen	SGU	MSc	F	Geologist
	Sandra Ó. Snæbjörnsdóttir	UoI	MSc	F	Geologist
	Anja Sundal	UiO	PhD	F	Postdoctoral Fellow
	Per Aagaard	UiO	PhD	M	Professor Emeritus
	Per Bergmo	SINTEF	MSc	M	Task Leader
	Benjamin Udo Emmel	SINTEF	PhD	M	Research Scientist
	Sigurdur R. Gislason	UoI	PhD	M	Professor
	Peter Frykman	GEUS	PhD	M	Senior Researcher
	Carsten Møller Nielsen	GEUS	MSc	M	Reservoir Engineer
	Yuefeng Gao	UiO	MSc	M	Research Assistant
	Irfan Baig	UiO	MSc	M	Research Assistant
	Irfan Baig	UiO	MSc	M	Research Assistant

Affiliation explanations

Chalmers	Chalmers University of Technology	SWEDEN
GEUS	Geological Survey of Denmark and Greenland	DENMARK
IVL	IVL Swedish Environmental Research Institute	SWEDEN
NTNU	Norwegian University of Science and Technology	NORWAY
SGU	The Geological Survey of Sweden	SWEDEN
SINTEF	Foundation for Industrial and Scientific Research at NTNU	NORWAY
Tel-Tek	Tel-Tek	NORWAY
UiO	University of Oslo	NORWAY
UoI	University of Iceland	ICELAND
VTT	VTT Technical Research Centre of Finland	FINLAND

Financing Plan

The three tables below summarize the funding plan for the NORDICCS project. The bottom table is the summary of the cash funding (upper table) and the in-kind funding (middle table). Total funding planned for the project was NOK 48,932,000.

CASH	2011	2012	2013	2014	2015	Total
Nordic Innovation	3 168 421	9 505 264	8 694 737	8 565 789	5 065 789	35 000 000
Statoil	300 000	300 000	300 000	300 000		1 200 000
Gassco	300 000	300 000	300 000	300 000		1 200 000
Reykjavik Energy						0
Norcem						0
TCM		300 000	300 000	300 000	300 000	1 200 000
Vattenfall			150 000	150 000	150 000	450 000
Total	**3 768 421**	**10 405 264**	**9 744 737**	**9 615 789**	**5 515 789**	**39 050 000**

IN-KIND	2011	2012	2013	2014	2015	Total
SINTEF ER	140 625	281 250	281 250	281 250	140 625	1 125 000
SINTEF PR	63 750	127 500	127 500	127 500	63 750	510 000
GEUS	79 900	159 800	159 800	159 800	79 900	639 200
SGU	43 900	87 800	87 800	87 800	43 900	351 200
Univ. Oslo	40 600	81 200	81 200	81 200	40 600	324 800
Univ. Iceland	50 000	100 000	100 000	100 000	50 000	400 000
Tel-Tek	98 050	196 100	196 100	196 100	98 050	784 400
IVL	47 900	95 800	95 800	95 800	47 900	383 200
Chalmers	90 375	180 750	180 750	180 750	90 375	723 000
VTT	75 400	150 800	150 800	150 800	75 400	603 200
NTNU	27 000	54 000	54 000	54 000	27 000	216 000
Mgmt - SINTEF ER	100 000	200 000	200 000	200 000	100 000	800 000
Statoil	0	0	0	0	0	0
Gassco	0	0	0	0	0	0
Reykjavik Energy	300 000	300 000	300 000	300 000	0	1 200 000
Norcem	300 000	300 000	300 000	300 000	0	1 200 000
TCM	0	0	0	0	0	0
Vattenfall		1 000	207 000	207 000	207 000	622 000
Total	**1 457 500**	**2 316 000**	**2 522 000**	**2 522 000**	**1 064 500**	**9 882 000**

TOTAL BUDGET	2011	2012	2013	2014	2015	Total
Cash	3 768 421	10 405 264	9 744 737	9 615 789	5 515 789	39 050 000
In-kind	1 457 500	2 316 000	2 522 000	2 522 000	1 064 500	9 882 000
Total	**5 225 921**	**12 721 264**	**12 266 737**	**12 137 789**	**6 580 289**	**48 932 000**

Budget

The table below shows the cash budget for the NORDICCS project. The total cash budget was NOK 39,050,000.

PARTNER/Year	2011	2012	2013	2014	2015	Sum
SINTEF Energy Research	852 000	1 587 000	1 482 000	1 509 000	1 490 000	6 920 000
SINTEF Petroleum Research	139 000	775 000	721 000	850 000	345 000	2 830 000
Centre Support	800 000	800 000	894 000	800 000	950 000	4 244 000
Meeting cost all	200 000	200 000	200 000	200 000	200 000	1 000 000
GEUS	175 000	922 000	887 000	907 000	515 000	3 406 000
SGU	112 000	529 000	475 000	361 000	216 000	1 693 000
Univ. Oslo	109 000	493 000	438 000	469 000	251 000	1 760 000
Univ. Iceland	109 000	572 000	537 000	568 000	350 000	2 136 000
Tel-Tek	178 000	1 062 000	1 203 500	1 309 500	508 000	4 261 000
IVL	248 000	587 000	603 000	515 000	135 000	2 088 000
Chalmers	168 000	953 000	978 000	998 000	518 000	3 615 000
VTT	168 000	815 000	800 000	820 000	414 000	3 017 000
NTNU	89 000	310 000	265 000	285 000	131 000	1 080 000
Subcontractors	0	250 000	250 000	250 000	250 000	1 000 000
Total	**3 347 000**	**9 855 000**	**9 733 500**	**9 841 500**	**6 273 000**	**39 050 000**

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Glossary

AWP	Annual Working Plan
C	Celsius
CA	Consortium Agreement
CAPEX	Capital expenditure
CCS	CO_2 capture, transport and storage
CCSP	Carbon Capture and Storage Program (Finland)
CMG	Centre Management Group (CMT plus Work Package Leaders)
CMT	Centre Management Team
CO_2	Carbon Dioxide
EGR	Enhanced gas recovery
EOR	Enhanced oil recovery
ETS	Emissions trading system
€/t	Euro per tonne
EU	European Union
Ex	Explosive area
g	Gramme
GIS	Geographical information system
IEA	International Energy Agency
k	Thousand
kg	Kilogramme
km	Kilometre
kt	Kilotonnes
kWh	Kilowatt hour
m	Metre
M	Million
MDEA	Methyldiethanolamine
MEA	Monoethanolamine
Mt	Million tonnes
Mtpa	Million tonnes per annum
NETP	Nordic Energy Technology Perspectives
NORDICCS	Nordic CCS Competence Centre
OPEX	Operational expenditure
SG	Steering Group
t	Tonne
TRI	Top Level Research Initiative
UK	United Kingdom
US	United States
yr	Year
WP	Work Package

The NORDICCS project
has been a Nordic CCS platform involving major CCS stakeholders in five Nordic countries, operating under the Top-level Research Initiative. The main objective of NORDICCS has been to contribute in boosting the deployment of CCS in the Nordic countries by creating a durable network of excellence integrating R&D capacities and relevant industry.

This report primarily summarizes the results and achievements from the project with focus on the six work packages: Assumptions and premises (WP1), Communication (WP2), Case studies (WP3), CO_2 capture (WP4), CO_2 transport (WP5), CO_2 storage (WP6), and Centre management (WP0). The main deliverables are the Nordic CSS Roadmap and the Nordic CCS Storage Atlas.

Total funding was MNOK 48.9, including MNOK 9.9 in in-kind contributions, and 17 partners participated. The project produced 113 publications, organized 15 public seminars and two CCS Summer Schools for young researchers, and issued nine newsletters and a project website.

The Top-level Research Initiative
is the largest joint Nordic research and innovation initiative to date. The initiative aims to involve the very best agencies and institutions in the Nordic region, and promote research and innovation of the highest level, in order to make a Nordic contribution towards solving the global climate crisis.

Top-level Research Initiative

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