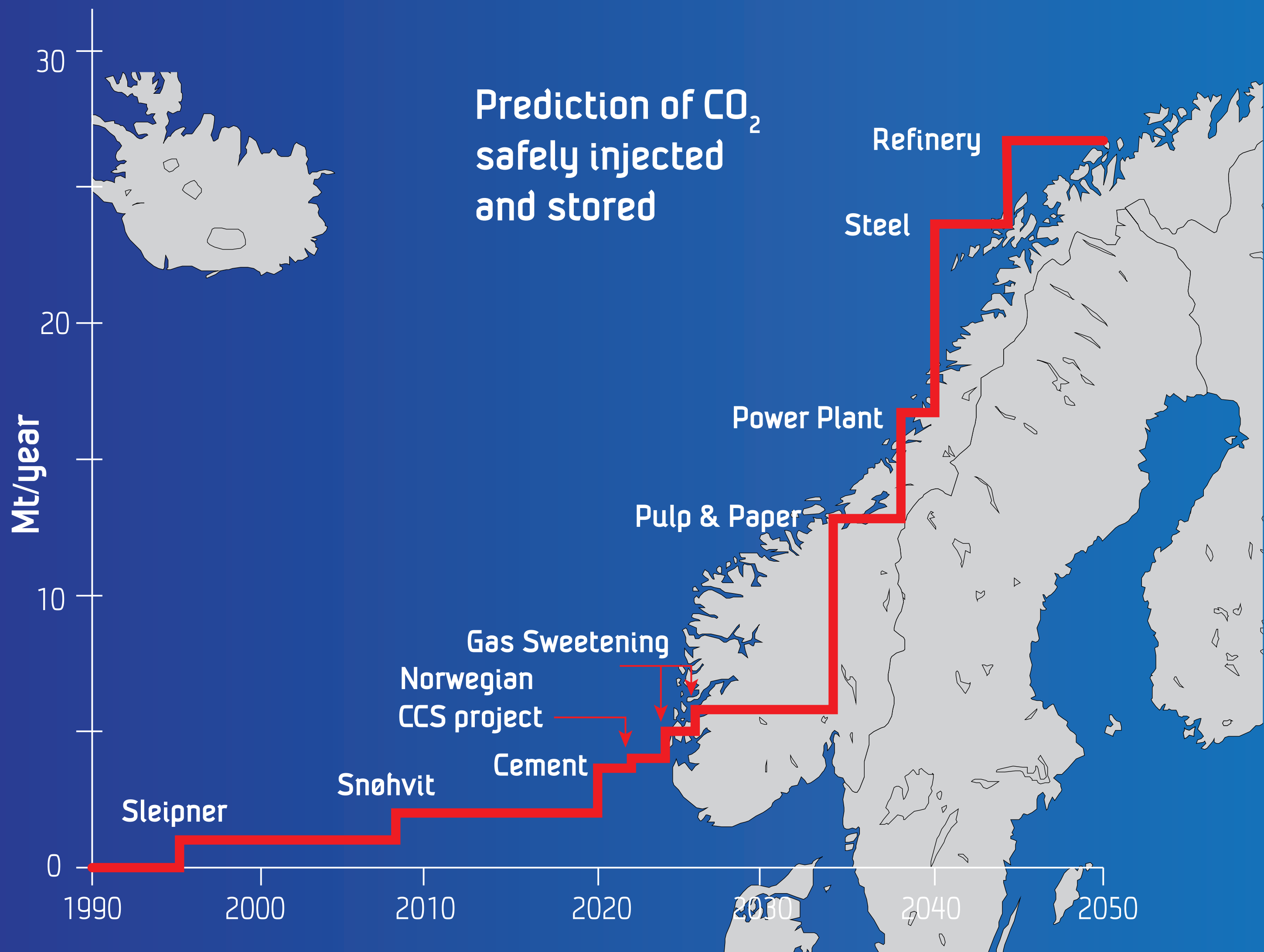
Nordic CCS Roadmap

Update 2015

A vision for Carbon Capture and Storage towards 2050



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The NORDICCS CCS Centre
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NORDICCS promotes the realization of CCS in industry and society as a whole. This is accomplished by pooling knowledge, exploiting RD&D results, utilizing industry experience, and sharing information between stakeholders.

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Content

Key conclusions

- Much of Nordic industry is 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 also 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 already has three CCS projects operational – two with geological storage – with more in the planning.
- 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 (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 cut costs dramatically through economies of scale. Indeed, **NORDICCS estimates the cost of storing the first 3 million tonnes (Mt) of CO_2/year to be only 517 M€ in CAPEX, which results in a storage cost of 15€/tonne**. The cost of building a second well to store an extra 3 Mt of CO_2/year is 92.5 M€. Three additional wells therefore mean a total of 12 Mt of CO_2/year can be 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 Skagerak 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 and Norway already has 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, including:
  - **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 opportunity to store CO_2
  - **Prioritising products with a low-carbon footprint in governmental project purchasing,** e.g. green cement, steel and aluminium
  - **Establishing a Measurement Reporting Guideline which allows CO_2 transport by ship** under the EU Emissions Trading System (EU ETS)
  - Establishing CCS support measures until the 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
  - Using the CO_2 hub to kick-start CO_2-EOR in the North Sea and reduce the costs of CCS even further – recognising that the window of opportunity is narrowing
  - 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.

1 The NORDICCS project: update

Climate change is accelerating even faster than predicted

It is generally accepted that CO_2 emissions must be drastically reduced in order to limit the rise in average global temperature to 2°C – and avoid irreversible climate change. In fact, the climate is showing signs of worsening even faster than predicted: in 2015, India experienced the fifth deadliest heat wave in the world, killing over 2,500 people.[1] With the average temperature above 50°C for days, a new colour had to be added to the average temperature map where purple now means over 50°C.

Extreme rain causing flooding in Alfta, Sweden. (Photo: Leif Larsson/TT/ NTB Scanpix)

The Nordic region, too, has seen extreme rains, flash flooding and mud-slides – and this will only increase, according to the Norwegian Metrological Institute. The amount of rain in Norway has increased by 18% since 1900 (measurements began in 1880) and is projected to increase by a further 10% by 2050.[2]

The Nordic countries have responded decisively by aligning with the Carbon-Neutral Scenario in the IEA's "Nordic Energy Technology Perspectives (NETP)" in which GHG emissions must be reduced by 85% by 2050 (versus 1990 levels) with carbon credits used to offset the remaining 15%.[3]

Nordic climate targets cannot be met *without* CCS

A unique characteristic of the Nordic region is that its energy supply relies on an extensive amount of renewable hydro and nuclear power. Electricity generation is therefore characterised by relatively low CO_2 emissions of ~100 g CO_2 per kWh – considerably lower than the global average of 550 g/kWh and the EU average of 430 g/kWh.

Industry, however, is still very dependent on fossil fuels and in some sectors, such as steel and cement, CCS is the only means of achieving deep emission cuts. This means that a minimum of 20 Mt of CO_2/year must be captured and stored in the Nordic countries by 2050, according to IEA scenarios in NETP. An analysis by VTT goes even further at 33 Mt CO_2/year by 2050.

With large CO_2 point sources in Sweden and Finland and vast CO_2 storage capacity off the coasts of Norway and Denmark, the region is ideally situated to deploy CCS. Indeed, developing joint infrastructure such as joint hubs and storage sites will not only result in significant economies of scale, but could create thousands of green jobs throughout the region.

CO_2 hub for shipment of liquid at Yara, Porsgrunn Norway – visit by NORDICCS CCS Summer School students (Photo: SINTEF)

CCS projects are now advancing rapidly worldwide

CCS technology is now advancing rapidly worldwide: 15 large-scale CCS projects are already operational, with 7 more under construction – double the rate since the start of this decade. A further 11 are at the most advanced stage of planning, with 12 more in the earlier stages.[4]

CCS projects are not only up and running in Norway (Sleipner, Snøhvit and Yara – with more in the planning), but also Iceland where 5,000 tonnes of CO_2/year is stored at the Hellisheidi power plant. The gas is of volcanic origin and the CO_2 is injected (dissolved in water) into the basaltic subsurface via the CarbFix method.[5]

CCS projects are also operational in the US, Canada (including the world's first large-scale power plant CCS project at Boundary Dam), Saudi Arabia and Brazil, while China has as many as 9 projects starting between 2017 and 2020.

Following the publication of the Nordic CCS Roadmap in 2013, the NORDICCS project has therefore now been updated to reflect up-to-date data from real plants and real projects on all elements of the CCS value chain – CO_2 capture, transport and storage.[6]

2 A joint CO_2 transport and storage hub will drive down costs

A North Sea storage site could become the CO_2 bank of Europe

Joint CO_2 transport and storage infrastructure in the North Sea will not only reduce costs dramatically through economies of scale, but could kick-start CCS in Europe. It involves relatively inexpensive 22,000 tonne ships transporting liquid CO_2 (at 7 bar and -50°C) to an onshore hub where it is unloaded, heated and re-pressurised for delivery by pipeline to the storage site (Figure 1).

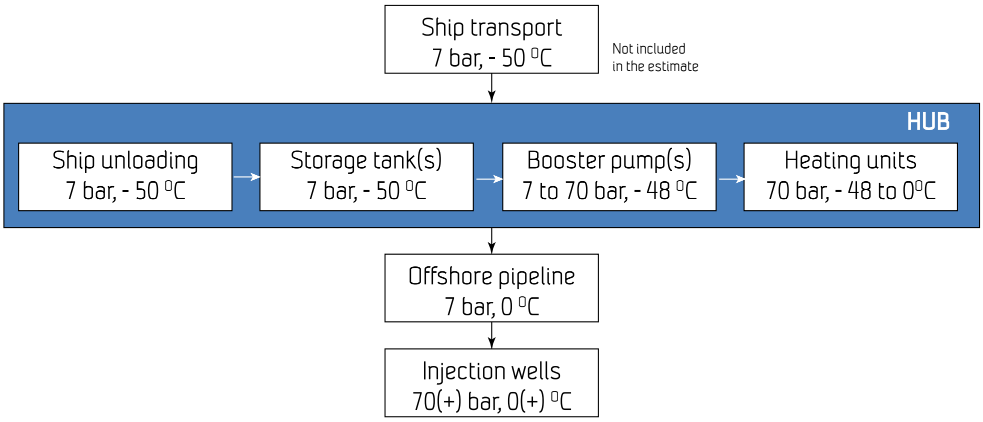

Figure 1: Joint CO_2 transport and storage infrastructure in the North Sea

Key benefits of an onshore hub

- Onshore off-loading is less weather dependent than offshore.
- Ships will also be much cheaper as the jetty will be equipped with unloading arms.
- A long pipeline will be built out to the storage site when profitable.
- This will also facilitate EOR by delivering a large and steady supply of CO_2 from the hub to nearby oil fields.

The Utsira formation: large, mature and cost-effective

Three potential storage sites have been particularly well evaluated in the Nordic region (Figure 2): the most mature is Utsira which is the best characterised site and has already been storing from Sleipner for nearly 20 years. Its high injectivity (3 Mt/year per well) also makes it the most cost-effective.

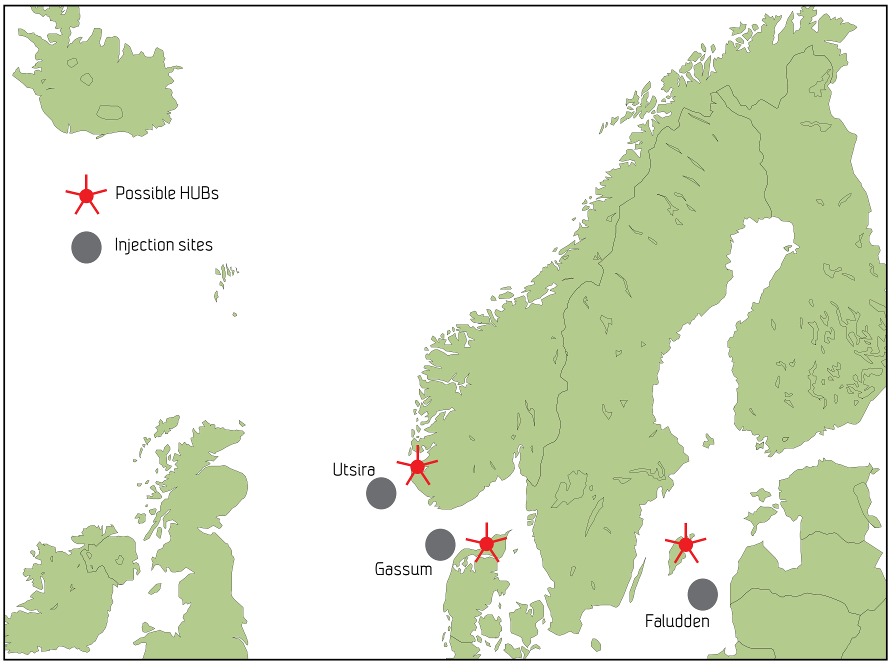

Figure 2: Potential hubs and storage sites in the Nordic Region

The Gassum formation in Skagerak is also fairly well-characterised and would be a natural second location if much of the surrounding industry starts storing CO_2. Finally, there is the storage site at Faludden, but injectivity is poorer and it could be less cost-effective for Nordic CCS projects.[7]

For the roadmap, all cases include ship transport to the joint storage site at Utsira. The proposed hub is placed outside Stavanger at as short distance as possible from the Utsira storage.

Ships are the lowest-cost transport option in 80% of Nordic cases

Transporting CO_2 by ship was the most cost-effective option in 80% of the 50+ cases analysed and the most appropriate for clusters during the ramp-up phase due to the extra cost and risk in building under-utilised pipelines. Norway already has extensive experience: Yara currently ships 200,000 tonnes of CO_2/year for sale to the European food and beverage industry. The cost of ship transport also increases only moderately with increasing distance. Combined with the low injectivity and storage capacity of reservoirs in the Baltic Sea, it may therefore be more economical to transport CO_2 by ship 800-1,300 km west for storage in the Gassum or Utsira formations.

Jetty with (un)loading arms Photo: Shutterstock

However, for distances shorter than 100 km and volumes larger than 1 Mt CO_2/year (e.g. a typical collection system containing multiple coastal sources) onshore pipeline will, in most cases, be the most cost-effective transport solution.

In some regions, pipeline transport may also be economical due to the close proximity of storage sites – particularly in the Skagerak region. The cost of pipeline transport was found to decline rapidly with increasing volume – potentially well below €10/tonne of CO_2 under certain conditions for sources located in the Kattegat-Skagerak region.

The pipeline volumetric breaking point was calculated for eight sites in the Nordic region. The break point refers to the volume required for the pipeline to become the least costly transport mode from that particular site. Thus any source connecting to a hub at that site should use ship transport until the required (shown) volume has been reached. Table 1 shows the pipeline volumetric breaking point/cost for transport to both the Gassum formation and the southern parts of the Utsira formation for three selected sources in the Nordic region. (Data is from the recent NORDICCS report by Kjärstad et al.[8])

Table 1: Pipeline volumetric breaking point and corresponding costs for three selected sources in the Nordic region

Site	Ship transport cost (€/tonne)	Breaking point with pipeline (Mtpa)
Brevik	13	4.0
Lysekil	12	5.0
Hvidovre	13	9.0

The cost of building an onshore hub + offshore storage is very favorable

The cost of the hub, pipeline and storage infrastructure was calculated using the following assumptions:

- Injectivity: 3 Mt CO_2/year per well
- Distance from hub to storage site: 200 km
- An existing site (i.e. no land cost, using existing utilities and buildings)
- Rate of return: 7.5%
- Project lifetime: 25 years
- Location factor: 1 (Rotterdam)
- Cost level: 2015

Three scenarios were considered when sizing the pipeline:

- Maximum case: up to 22 Mt CO_2/year (the largest available offshore pipeline is 48 inch diameter)
- Medium case: up to 12 Mt CO_2/year
- Minimum case: up to 3 Mt CO_2/year

As can be seen from Figures 3 and 4, the pipeline only transporting 3 Mt CO_2/year is not as cost-effective as the larger ones. This is to be expected due to the impact of economies of scale. For every 3 Mt/year stored a new pipeline and well must be built – hence costs will increase linearly with time.

However, the Medium case is as economically viable as the Maximum case yet requires less upfront investment. In this case, the pipeline can transport up to 12 Mt CO_2/year, enough to feed 4 wells of 3 Mt CO_2/year each. When this pipeline is up to capacity, a new 12 Mt pipeline must be built. The Maximum size pipeline has a larger capital expenditure (CAPEX) and it takes 12 Mt CO_2/year stored to achieve the same economic viability as the Medium case. The Medium case was therefore selected as the most optimal.

The NORDICCS project therefore estimates the infrastructure costs for an onshore hub + pipeline + 1 well injecting 3 Mt of CO_2/year and offshore storage (maximum 12 Mt of CO_2/year) as follows:

- CAPEX: 517 M€
- OPEX: 7.75 to 4.50 M€/year
- Deposit cost is 15€/t CO_2

The cost of building a second well to store an extra 3 Mt of CO_2/year is 92.5 M€. Three additional wells therefore mean a total of 12 Mt of CO_2/year can be stored. If the Nordic countries share the initial investment of only 517 M€ in infrastructure, costs will be very favorable. Utsira is large enough to receive CO_2 not only from CCS projects throughout the Nordic region, but also Northern Europe. In fact, CCS deployment can start as soon as the infrastructure is ready to receive the CO_2.

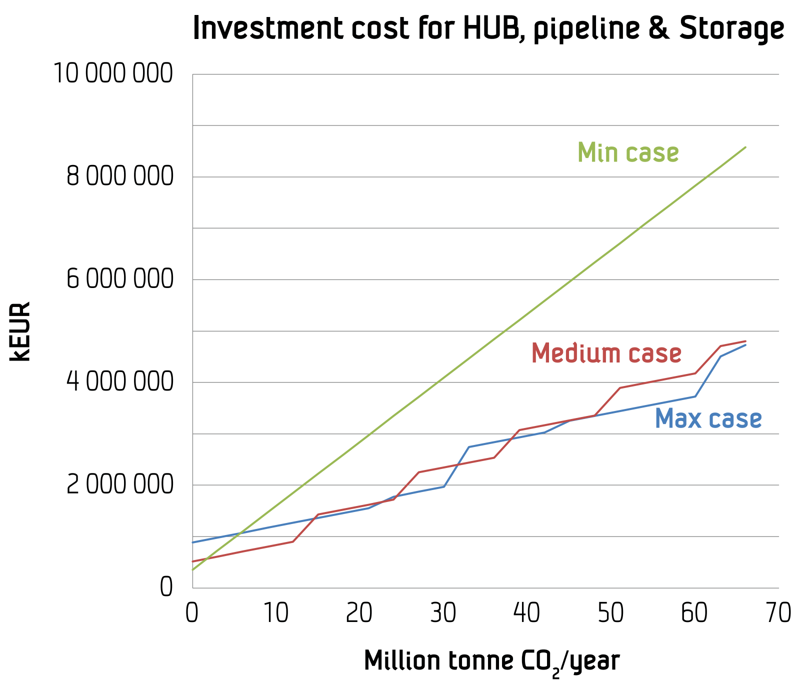

Figure 3: Investment costs for hub, pipeline and storage

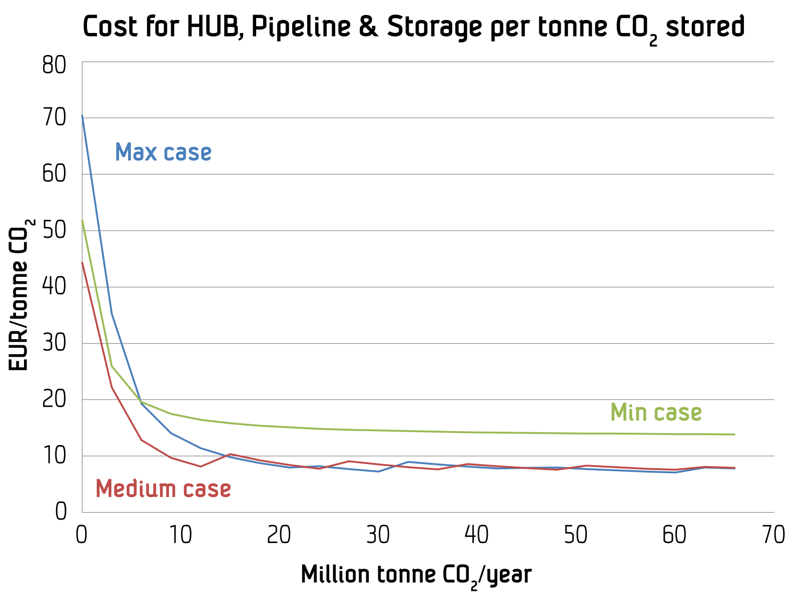

Figure 4: Unit costs for hub, pipeline and storage

3 The most cost-effective solutions for CCS deployment

Large-scale projects benefit from significant economies of scale

In order to determine the most cost-efficient solutions for CCS deployment, economic analyses were performed for 50+ cases in the Nordic region. Most were relatively large-scale projects (>300 tonnes of CO_2), where economies of scale reduce the cost per tonne of CO_2 stored (Figure 5 shows the main point sources).

Estimated costs for capturing, transporting and storing CO_2 for selected cases are shown in Figure 6, divided into capture, transport and storage.

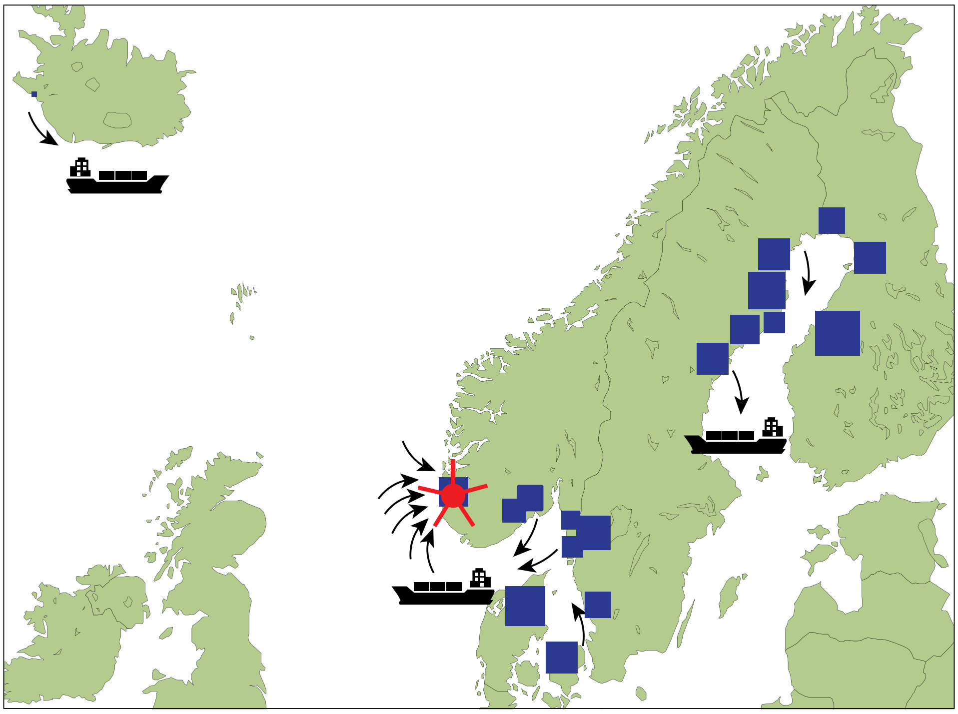

Figure 5: Sources of CO_2 in the Nordic region

Assumptions were as follows:

- Capture costs assume the use of the generic Tel-Tek MEA process, except in the case of natural gas sweetening where MDEA is used (see Table 2 for examples of capture costs for the Skagerak cluster).
- In calculating CAPEX, it was assumed that the plant (with CCS) is n^{th}-of-a-kind. Although the first plants will be more expensive, it is more appropriate to determine what is most economical in the long term.
- All costs were calculated using the 2012 cost level for euros.
- Escalation was based on the Consumer Price Index (CPI) in Eurostat.
- Rate of return was set to 7% and project lifetime to 25 years.

Cost estimates also include a ‘location factor’ adjustment that represents either a certain industry or location. Factors that will typically increase the cost of a construction project are special considerations such as additional costs for oil and gas offshore, and refineries onshore due to the explosion hazard. Other factors that increase costs are remoteness (i.e. it costs money to transport personnel and goods to remote construction sites) and inclement weather.

For further details of the methodology used and detailed cost analyses, see the NORDICCS report by Skagestad et al.[9]

Natural gas sweetening: the most economically viable option

The roadmap analysis shows that natural gas sweetening (i.e. removing more CO_2 from natural gas before it is exported) is the most economically viable case for CCS (see Figure 6)

Capture costs are the lowest partly because sweetening uses the less costly capture process, MDEA (as opposed to the MEA process used in other industrial CCS projects). This is due to higher pressures which result in reduced absorber size and higher input pressure to the CO_2 compressor, significantly reducing both electricity consumption and investment costs. It is reasonable to assume that a natural gas sweetening project will be close to a storage site, resulting in minimal transportation costs.

The case evaluated represented a generic case: 1.15 Mt of CO_2/year was captured with a CO_2 concentration of 10% in the natural gas. This is similar to the properties of the capture process currently ongoing at the Sleipner and Gudrun fields. There are several more undeveloped gas fields on the Norwegian Continental Shelf with relatively high CO_2 content[10] that could be developed if the CO_2 was removed from the natural gas and stored.

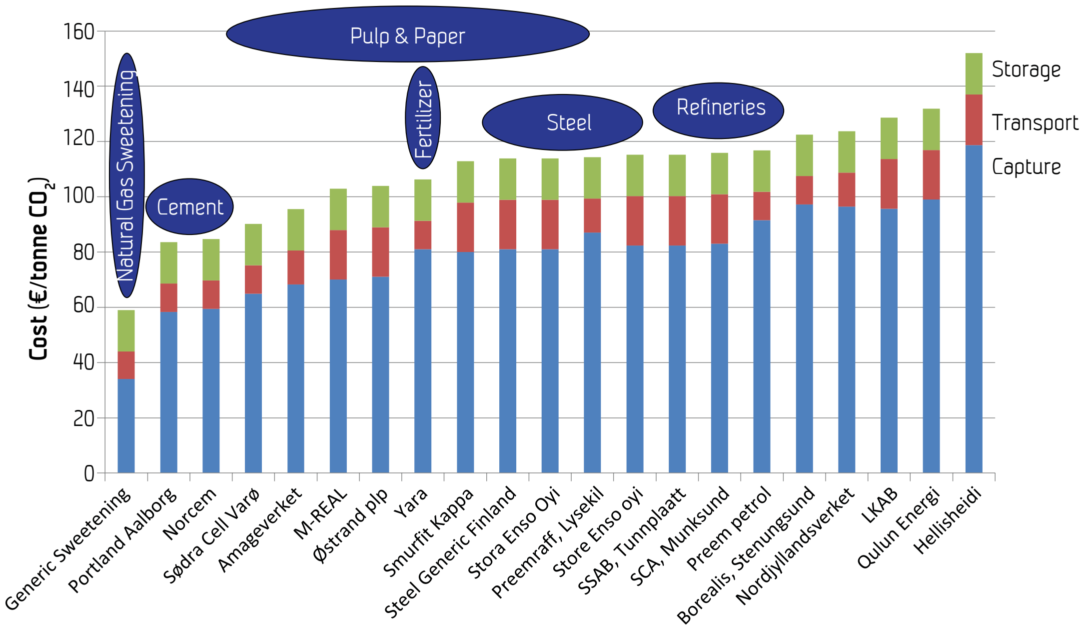

Figure 6: Estimated costs for capturing, transporting and storing CO_2 for selected cases (totalling 26 Mt in line with Nordic climate goals).
- **Costs calculated using MEA process, except for Sweetening, MDEA**
- **Capture costs can be reduced significantly by utilizing waste heat from steel & cement plants, not included here**

Industrial CCS: CO_2 clusters with joint storage lead to lowest costs

Many of the cases were clustered in areas with major industrial activity such as Skagerak, the Bay of Bothnia and the east coast of Sweden. For all cases, transport costs were calculated from the point source to the onshore hub, outside Stavanger, as close to the most mature and cost-effective offshore storage site at Utsira as possible.

Source	CO_2 emissions, Kt/y	CAPEXgeneric, M€	OPEX generic, M€	Capture cost generic, €/t	Location factor	Capture cost local, €/t
Norcem, Brevik *Cement*	927	143	49	54	1.1	59
Yara Porsgrunn *Chemicals*	815	135	43	60	1.4	81
Preemraff, Lysekil *Refinery*	1,670	254	86	58	1.5	87
Borealis Krackeranl., Stenungsund *Chemicals*	690	157	42	72	1.4	97
Aalborg Portland, Nordjylland *Cement*	1,150	204	73	53	1.1	58
Nordjyllandsverket *Heat and power*	2380	245	108	63	1.5	96

Table 2: Capture costs for potential CCS projects in the Skagerak cluster (Case 2).

In the Skagerak industry cluster, CO_2 sources are not only located in close proximity, but within a short distance of a potentially joint storage site in the Gassum formation on the Danish continental shelf, or via easy ship transportation to Utsira. The potentially large scale of this cluster could also make it a candidate for CO_2-EOR projects in nearby oil fields, thus reducing costs even further.

CO_2 storage in basaltic rocks: a key opportunity for technology export

The Hellisheidi geothermal power plant in Iceland stores 5 kt of CO_2/year in basaltic rocks with which the CO_2 reacts to form a solid carbonate; the cost of capture is estimated to be 104 €/tonne of CO_2.

This could represent an important opportunity for technology export to other regions, such as India, which has an extensive amount of basaltic rock structures which could also be used for CO_2 storage.

The Portland cement plant in Ålborg, Denmark and the Norcem cement plant in Brevik, Norway, have among the lowest-cost CCS projects evaluated (see Figure 6). The Norcem cement plant emits 0.8 Mt of CO_2/year and has 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 to make CO_2 capture more economically viable.[11] However, for this report, the cost estimate has been based on publicly available information on the process and 0.8 Mt of CO_2 captured. The cost of capture considering the location factor is 59€/tonne of CO_2.

The Norwegian Government (via Gassnova) awarded Norcem a feasibility study for the commercialisation of CCS at their cement plant in Brevik in October 2015. A project testing four capture technologies was also conducted at Brevik, after which a feasibility study is moving forward with the most mature amine technology from Aker Solutions.[12] Portland Aalborg has a larger cement plant emitting 1.15 Mt of CO_2/year and an estimated capture cost of 57 €/tonne. In both cases, transport and storage costs are based on shipping the CO_2 to Utsira.

The pulp and paper industry accounts for a large proportion of Nordic emissions, particularly in Sweden and Finland. One of the larger point sources can be found at the SCA Östrand pulp mill in Northern Sweden which emits 1.4 Mt of CO_2/year: the cost of CO_2 capture, including localisation factors, is 71 €/t. Other large sources for the paperboard, biomaterials, wood and packaging industry include M-real (Matsa paperboard) Sweden (1.7 Mt/year), Iggesund Paperboard (0.8 Mt), Sødra Cell Varø (1 Mt) and Stora Enso (1.6 Mt): the costs of capture are 70-80 €/tonne of CO_2.

Bio-CCS is a relatively effective and economic means of removing some of the CO_2 emissions that are already locked-in by existing industries with no other mitigation options available, with the potential for both bio-industry and bioenergy applications in the Nordic countries. By capturing and storing biogenic CO_2 offshore in Norway and Denmark, large-scale carbon negative projects are therefore feasible. Indeed, it may be a necessity in order to ensure 2050 goals are met.

Other Nordic industries with significant emissions are steel and refineries, with a generic steel plant in the Bay of Botnia having a capture cost (including localisation factors) of 81 €/t. It must be noted that capture costs for a steel mill can also be significantly reduced if the capture plant is integrated with the steel mill's processing and power production.[13] Generally, the costs of capture can be reduced for any project if there is the opportunity to integrate the capture process and utilise heat from other processes at the project plant. One refinery case was also considered in detail: the Preem refinery in Lysekil which emits 1.7 Mt of CO_2/year.

There are also some power plants which are large emitters, such as Nordjyllandsverket, Fortum F&H and Amagerverket. The latter emits 1.5 Mt CO_2/year near to a potential storage site at Havnsø in Denmark; capture cost is 68 €/tonne of CO_2.

4 Urgent action is needed to ensure climate targets are met

Create public investment in the first joint CO_2 hub and storage site in the North Sea

In order to kick-start CCS deployment, upfront public investment is needed in the first transport and storage hub in the North Sea – shared by the Nordic governments and where all the Nordic countries have opportunities to store CO_2.

In Norway, the Department of Oil and Energy through Gassnova has already issued contracts for feasibility studies on CCS at NORCEM cement factory in Brevik, the Waste-to-Energy Agency in the City of Oslo and plan to enter into agreement in the near future with Yara for the ammonia plant in Porsgrunn. In addition a request for bids for a CO_2 storage feasibility study has been issued in November 2015. Gassco will handle the transport part of the feasibility studies. All the feasibility studies should conclude in concrete plans for a full-scale CCS value chain by 2017 in order to meet the Government's goal of a full-scale project in Norway by 2020.

Prioritise products with a low-carbon footprint in governmental project purchasing

In order to implement CCS in Nordic industries such as cement and steel – which are very price competitive – it may be necessary for governments to base competitive bids on carbon footprint ahead of cost so that green materials produced with CCS are given priority. This would make it possible for producers such as Norcem to progress with the first plant in the world to produce cement with CCS, setting a new technology standard for the industry and creating additional jobs.

Strengthen the EU ETS as the long-term driver for CCS

The EU Emissions Trading System (ETS) is the long-term driver for CCS, but it is currently not effective as the cost of emission unit allowances is too low. The ETS should be therefore be strengthened, while addressing the following issues as a matter of urgency:

- There is currently no incentive to capture and store biogenic CO_2 emissions – they should be rewarded under the ETS on the same basis as fossil CCS.
- The transport of CO_2 by ship is currently not allowed under the ETS – only by pipeline. This is a problem (e.g. in the Skagerak area), because Nordic CCS projects may require CO_2 to be shipped from sources in Sweden and Finland across national borders for offshore storage in Denmark and Norway. In order for shipping to be allowed under the ETS Directive, a Measurement Reporting Guideline (MRG) must therefore be established.

Establish support measures to make CCS commercially attractive

Until the ETS can deliver a meaningful carbon price, support measures are essential to make CCS commercially attractive. As with any large complex project, CCS incurs significant financial risk, involving not only the cost of establishing the project (CAPEX), but also the additional operational costs over the lifetime of the project (40+ years).

Capital grants have been key to the implementation of large-scale CCS projects in US and Canada, which is reasonable since a 'first-of-a-kind' unit will always be more expensive than an 'n^{th}-of-a-kind' unit.

Use the CO_2 hub to kick-start CO_2-EOR and reduce costs even further

Extensive offshore storage capacity off the coasts of Denmark and Norway, combined with an existing infrastructure of offshore oil and gas fields, provide the Nordic region with a unique opportunity to reduce the costs of CCS projects via CO_2-EOR.

There have already been attempts to start EOR projects on the Norwegian Continental Shelf. In 2009, Maersk Oil planned to use CO_2 from a Finnish power plant and ship it to the North Sea for injection into a depleted oil or gas field for the purposes of EOR/EGR. However, this project was abandoned in 2011 as insufficient amounts of CO_2 were captured to meet the needs of the oil field, according to Maersk. Another example is Statoil's Gullfaks field, where a detailed EOR feasibility study was performed. However, this project was also deemed unfeasible due to the lack of a reliable supply of CO_2 (5 Mt/year).

The Norwegian Department of Oil and Energy has suggested that just 2-3 Mt of CO_2/year may be sufficient to kick-start offshore EOR projects. The creation of a joint, large-scale storage site at Utsira could provide such a supply of CO_2, from many different sources, thus creating a price for CO_2 similar to the US EOR market where it is currently sold at ~35 US$ tonne. This will give land-based Nordic industry a significant economic incentive to capture CO_2.

However, the window of opportunity is closing: urgent action is needed in order to make the best use of the remaining oil reserves in Norway, Denmark and the UK; if not, vital infrastructure for CCS will be lost as oil fields decline and are abandoned.

Glossary

C	Celsius
CAPEX	Capital Expenditure
CCS	CO_2 Capture and Storage
CO_2	Carbon Dioxide
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ETS	Emissions Trading System
EU	European Union
Ex	Explosive area
g	Gramme
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
OPEX	Operational expenditure
t	Tonne
UK	United Kingdom
US	United States
yr	Year

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