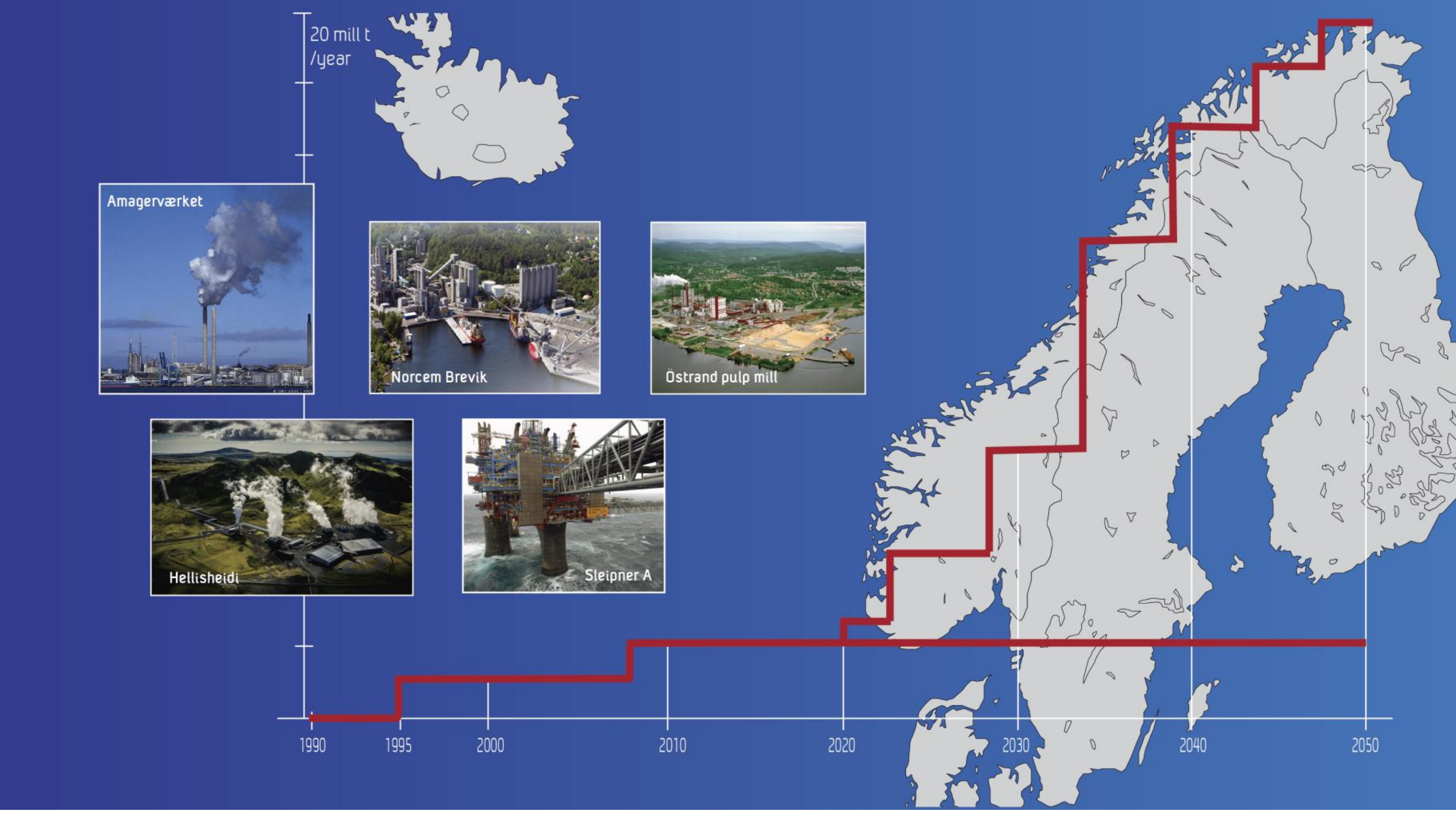

CCS case synthesis

Final Report

Ragnhild Skagestad, Hans Aksel Haugen, Anette Mathisen

NORDICCS Technical Report D3.14.1501/D14

October 2015

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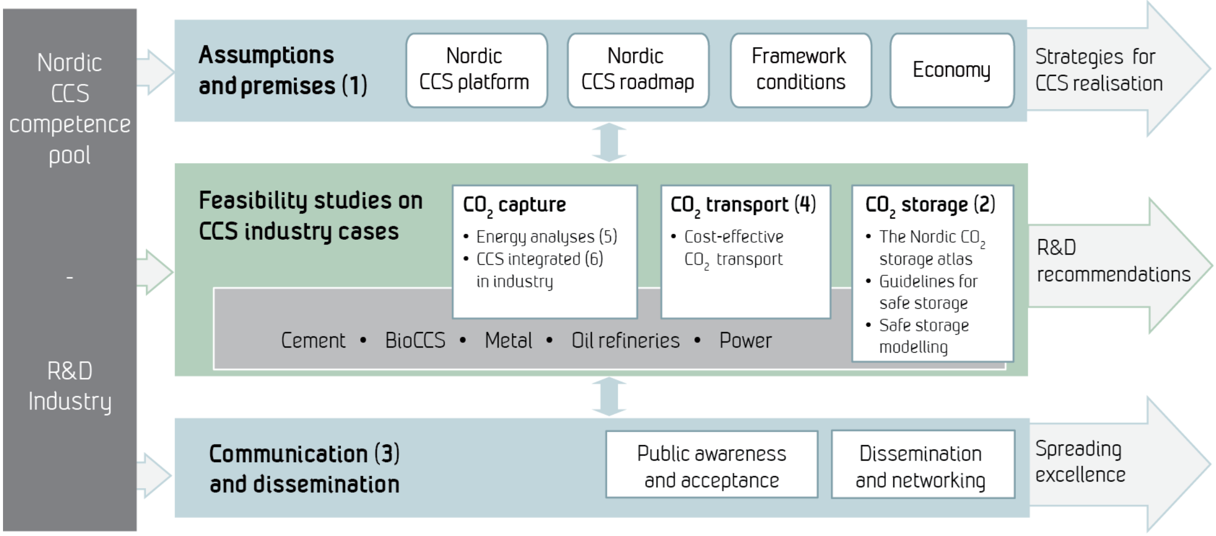
Nordic CCS competence pool - R&D Industry

Assumptions and premises (1)
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Summary

This report 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. 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.

Transport and storage are necessary parts of the CCS chain, but the capture cost is the dominating cost element. The cost of capture is mostly dependent CO_2 volume and to some extent CO_2 concentration of the flue gas.

The transport costs depend on the CO_2 volumes and the transport distance. For most of the studied CCS cases it was found that ship based transport network was the least costly solution. There are few cluster benefits when considering ship transport, however, cooperation on storage is necessary in order to reduce the storage costs. Storage costs have been proven hard to obtain, and a complicating factor is that the cost is very site specific. Reliable cost estimates for storage can only come from increased knowledge of the specific storage reservoir. The furthest developed and well known storage site is the Utsira Fm.

Based on the findings in this report it is clear that there is a need for cost reductions in all parts of the CCS chain. A step towards reducing the costs would be full-scale whole chain demonstration projects. The effect of clustering is found to be limited, but there is a definite potential for CCS in the Nordic region.

Keywords CCS implementation, Nordic industry

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EXECUTIVE SUMMARY

The NORDICCS project has outlined the technologies most attractive for CO_2 capture, transport and storage and provides a timeline for their implementation in the Nordic region. The objective of this report is to identify potential CCS cases in the region. Ultimately six cases were identified and investigated, and these are illustrated in Figure 1. The 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 that influence the cost estimation results, and this makes it difficult to draw any general conclusions. 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.

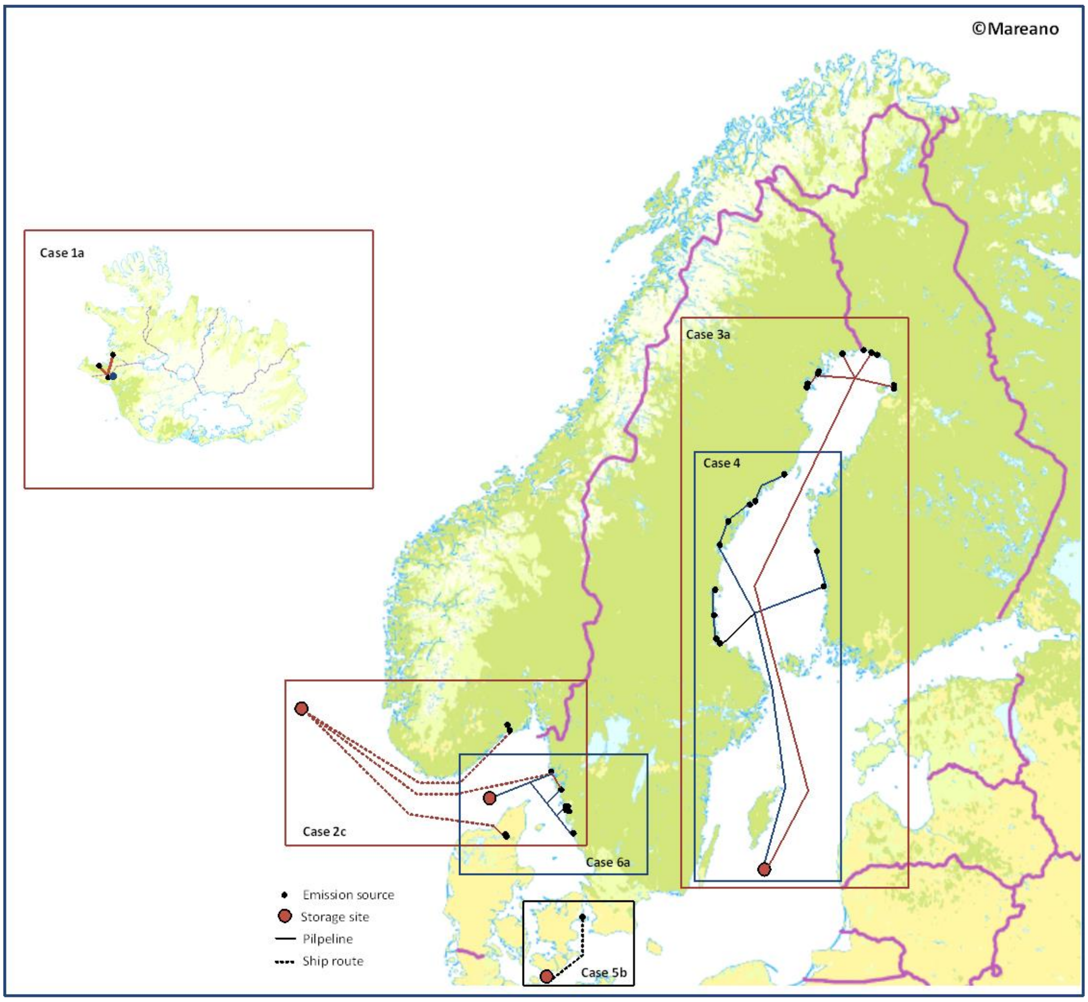

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Figure 1 Overview of the six cases in the Nordic Countries

Transport and storage are necessary parts of the CCS chain, but the capture cost is the dominating cost element. The cost of capture is mostly dependent on the CO_2 volume. The generic capture cost, with the current assumptions, primarily lies in the region of 55-90 EUR per ton. This 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 transport costs depend on the CO_2 volumes and the transport distance, and generally lie in the region of 12-20 EUR per ton. For most cases it was found that ship based transport network was the least costly solution, however, there are exceptions. In addition, it was found that some cases would benefit from having a transport network comprising both ship and pipeline. Transport over long distances favours ship over pipeline. The operational cost is higher for ship, but the sunk cost in pipelines is considerable and reduces the flexibility of the transport network. Flexibility of transport is likely to be needed as there are large uncertainties when it comes to the timeframe of implementation of CCS on individual plants and 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.

Storage costs have been proven hard to obtain, and a complicating factor is that the cost is very site specific. Reliable cost estimates for storage can only come from increased knowledge of the specific storage reservoir. Still, an effort was made to combine storage costs provided by ZEP and the storage sites identified in the NORDICCS project. The furthest developed and well known storage site is the Utsira Fm, which is therefore given the lowest cost, 7 EUR per ton. The other storage sites were, due to lack of information, given costs higher than Utsira, with cost ranging from 13 to 20 EUR per ton.

Based on the findings in this report it is clear that there is a need for cost reductions in all parts of the CCS chain. A step towards reducing the costs would be full-scale whole chain demonstration projects. The effect of clustering is found to be limited, but there is a definite potential for CCS in the Nordic region.

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INTRODUCTION

The industrial and power sectors are likely to be subjected to regulated CO_2 emission reductions in the short or medium term. These reductions can be achieved through several measures; increased energy efficiency, change towards less CO_2 intensive fuels and CCS, among others. It is probable that several of these measures will need to be implemented to varying degree. Solutions are therefore needed in order to find sustainable methods for carbon reduction and to minimize the associated costs. If industry take a proactive role in these matters, it is possible to reduce the threat that entire industry sectors being transferred to other countries with less stringent regulations regarding greenhouse gas emissions (carbon leakage).

NORDICCS is a CCS networking platform aiming for increased CCS deployment in the Nordic countries. The project will outline the technologies most attractive for CO_2 capture, transport and storage and provide a timeline for their implementation in the Nordic region. The objective of this work, within the NORDICCS project, is to identify potential CCS cases in the region. These cases are built up around geographically close emission sources that are likely to benefit from a shared transport and storage infrastructure. The cases are evaluated technically and economically in order to assess their suitability for CCS.

Methodology

The NORDICCS project is divided into several work packages (WP's) covering the technical aspects of the whole CCS chain and dissemination of results.

In the NORDICCS project structure, WP3 – Feasibility Study serves the role to combine the results from WP 4 - Capture of CO_2, WP 5 - Transport of CO_2 and WP 6 - Storage of CO_2, into relevant CCS chains for the power and industrial sectors in the Nordic region. The feasibility study has both an economic and a technical approach, and covers several types of industries, capture technologies, transportation methods and sinks. The outcome will benefit the sources that are the focus of the case study, the industry and power sectors as a whole and the governments in the Nordic countries.

Based on the findings from WP's 4, 5 and 6, WP 3 has performed CCS feasibility studies. In WP 4, six industrial sources have been selected for further studies, and these form the basis for the fully integrated CCS cases selected in the feasibility study. Figure 2 shows how the CCS cases are built up. The sources used in the case studies will be part of CO_2 clusters together with surrounding CO_2 emitters. Options for transport of the CO_2 captured and storage sites are then evaluated technically and economically for each cluster.

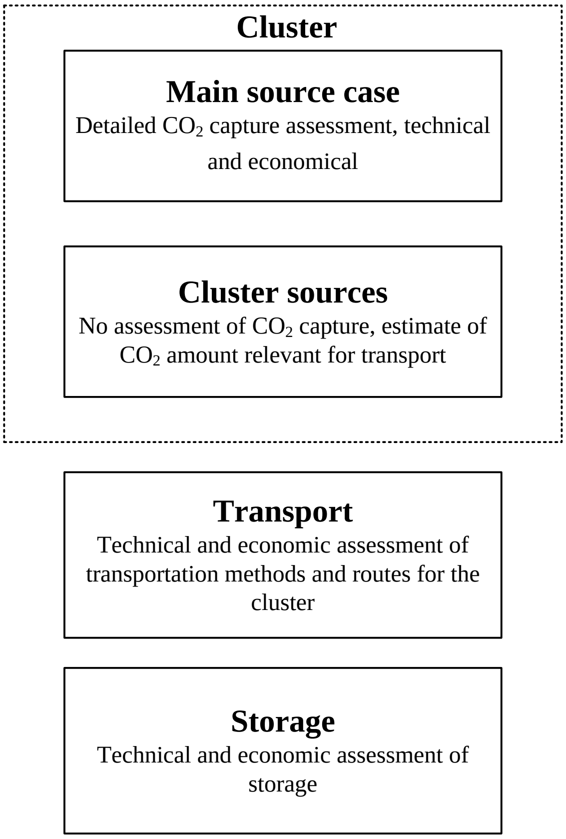

Figure 2 Elements in the CCS feasibility study

The surrounding sources that make up the cluster together with the main source are primarily selected based on geographical proximity to the main source. However, there are some deviations from this. The reasoning behind the selections will be given in under the more detailed description of the identified Nordic CCS cases.

CCS feasibility cases

The CO_2 emissions (2010 numbers) in the Nordic region have been mapped, and include an overview of CO_2 volumes emitted, location, and type of industry [1.]Storage sites in the Nordic region have been assessed and ranked. [18.] It was reported that three formations (Fm) on the Norwegian Continental Shelf (NCS) are the most promising for large-scale storage. These are the Utsira, Sognefjord and Skade Fm. The Gassum Fm offshore northern Denmark and the Faludden Fm in Sweden have also been identified, however new high quality data is needed to affirm their storage suitability and potential.

The complete integrated CCS chains have been developed guided by the following criteria;

- Emission sources will be chosen from all the Nordic countries and include industry relevant for the region

- Suggested capture technology at individual sites will be based on analysis of several capture technologies
- Suggested CCS chains will assess several storage and transport options including transport method (ship and/or pipeline)

In Table 1, an overview of the integrated CCS cases is provided. Each case is described in more detail in dedicated sections. There have been some changes in the CCS cases over the project period, but the main sources the main storage sites remain the same.

Table 1 CCS cases in the Nordic region

CCS case	Country	Main source	Cluster	Main transportation	Storage
1a Iceland	Iceland	Hellisheiði geothermal heat and power plant,Iceland	3 sources close to main source	Onshore pipeline	Basaltic rock in south western Iceland
1b Iceland	Iceland	Hellisheiði geothermal heat and power plant,Iceland	4 sources,	Ship	Utsira Fm
2a Skagerrak	Norway, Denmark, Sweden	Norcem Cement, Brevik, Norway	4 sources Medium sized cluster	Offshore pipeline	Gassum Fm
2b Skagerrak	Norway, Denmark, Sweden	Norcem Cement,, Brevik, Norway	4 sources Medium sized cluster	Offshore pipeline	Utsira Fm
2c Skagerrak	Norway, Denmark, Sweden	Norcem Cement,, Brevik, Norway	4 sources Medium sized cluster	Ship	Utsira Fm
2d Skagerrak	Norway, Denmark, Sweden	Norcem Cement,, Brevik, Norway	4 sources around the Skagerrak Basin. Medium sized cluster	Offshore pipeline	EOR to Gullfaks reservoir
3a Bay of Bothnia	Finland, Sweden	Generic steel plant northern shore of the Gulf of Bothnia, Finland	10 sources Large, compact cluster	Offshore pipeline	Faludden Fm
3b Bay of Bothnia	Finland, Sweden	Generic steel plant northern shore of the Gulf of Bothnia, Finland	10 sources Large sized cluster	Ship	Faludden Fm
4a North east of Sweden	Sweden, Finland	SCA Östrand pulp mill	11 sources Large elongated cluster	Offshore Pipeline	Faludden Fm
4b North east of Sweden	Sweden, Finland	SCA Östrand pulp mill	11 sources Large elongated cluster	Ship transport	Faludden Fm
5a Copenhagen	Denmark	Amagerværket Heat and power plant	Single source to sink	Onshore/ offshore pipeline	Bunter Fm
5b Copenhagen	Denmark	Amagerværket Heat and power plant	Single source to sink	Ship transport	Bunter Fm (Gedser)
5c Copenhagen	Denmark	Amagerværket Heat and power plant	Single source to sink	Onshore pipeline	Gassum Fm (Havnsø)
6a Lysekil	Sweden	Preem Petroleum, Refinery, Lysekil	6 sources Medium cluster	Offshore pipeline	Gassum Fm
6b Lysekil	Sweden	Preem Petroleum, Refinery, Lysekil	6 sources Medium cluster	Ship	Gassum Fm

All the CCS cases described in Table 1 are evaluated technically and economically and based on this their feasibility is assessed. Figure 3 gives an overview of identified sources and storage sites used in the CCS cases for the Nordic region.

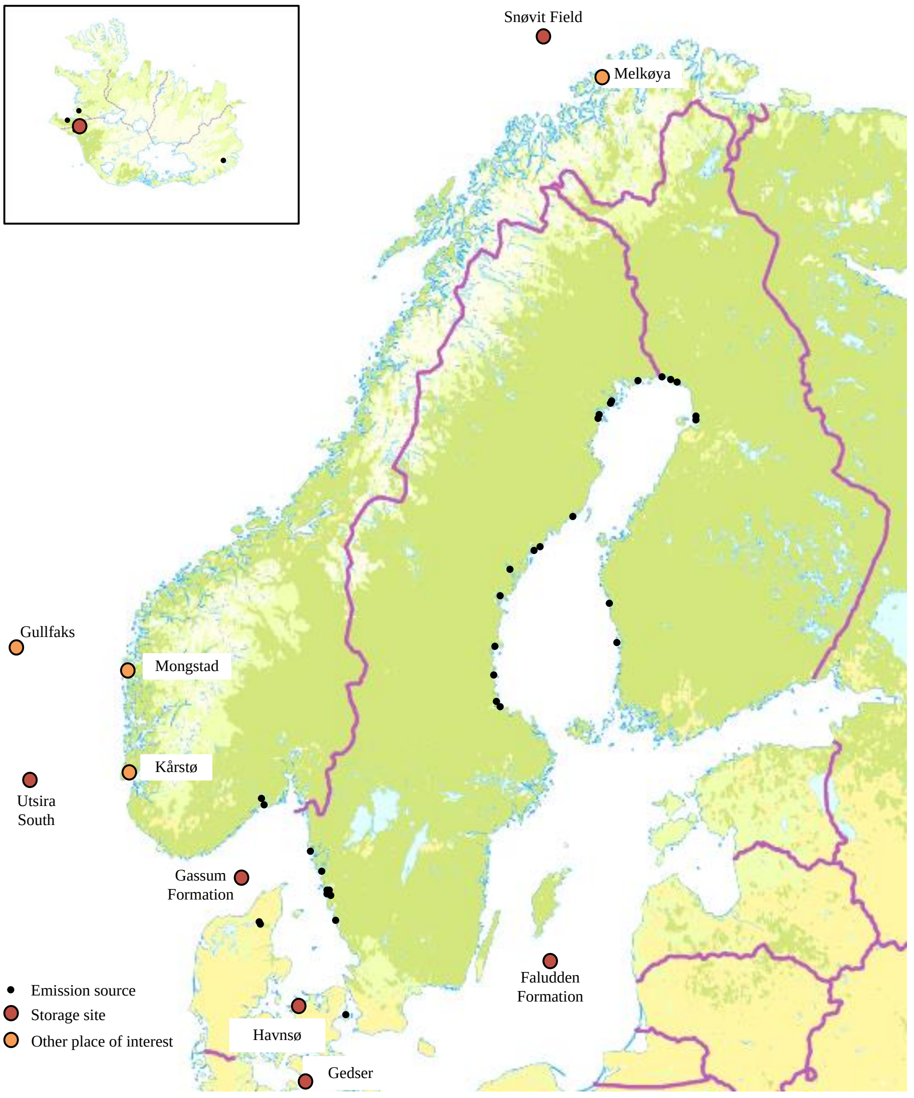

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Figure 3 CO_2 emission sources and possible storage sites in the Nordic Countries

ASSUMPTIONS

Technical

Capture

The basis of the technical and economic study is existing CO_2 emission sources in the Nordic region, and their yearly CO_2 emissions. The CO_2 amounts to be handled vary greatly for the different cases identified in Table 1. Part of the NORDICCS work investigates in detail the CO_2 capture possibilities for most of the selected main sources. The reader is referred to the NORDICCS report ”Industrial implementation of Carbon Capture in Nordic industry sectors”[5.] for details regarding the technical considerations. Beyond the main sources, all of the CCS cases except one, also consist of additional CO_2 emission sources that make up the cluster. These sources are called cluster sources and their 2010 CO_2 emission data are extracted from [1.]. These sources are only considered in a general sense, and the following assumptions are made regarding capture;

- The CO_2 is captured using post-combustion MEA technology (Tel-Tek developed model)
- 85% capture rate is assumed
- The CO_2 is delivered for transport at 70 bar and 20˚C
- No extra pre-treating of the flue gas (removal of SOx, NOx and dust)
- Flue gas is delivered at the boundary of the capture plant
- All utilities are brought to capture plant boundary

Post-combustion MEA is an energy intensive process. Steam must be supplied to the desorber reboiler to provide the heat for desorption of CO_2. In addition, energy is needed for the process gas fans and CO_2 compression. It is uncommon for industrial plants to have sufficient excess energy available for this purpose, however, they are likely to have some. In order to identify and quantify the excess energy potential for each plant, a detailed investigation is needed. This has not been undertaken for the cluster sources and a natural gas fired combined heat and power (CHP) plant is included as a part of the CO_2 capture facility. It is assumed that the CO_2 generated in the CHP plant is also captured.

Many of the CO_2 sources included in the feasibility study utilize biomass. In this report, no distinction is made between fossil and bio-based CO_2 when building up the cases. CO_2 capture from biomass can have large impact on the overall CO_2 emission reductions, but there are no specific economic incentives to capture CO_2 from biomass yet.

It is assumed that the physical space needed for the capture plant including the CHP is available. A detail investigation regarding future plans and layout for the individual sites is needed to validate this assumption.

Storage

Storage sites in the Nordic region were identified and assessed in the WP 6 work [17.] and [18.]. Potential sites have been identified in all the Nordic countries except for Finland. In Norway, Denmark and Sweden, the sites are sandstone formations. Iceland, on the other hand, is a special case where CO_2 is to be stored in basaltic rocks. There are still considerable uncertainties regarding the identified storage sites in regard to storage volumes and injection rates. Even though there are uncertainties, the following formations have been included in the feasibility study; the Utsira, Gassum, Faludden and Bunter Fm (Havnsø, and Gedser traps). The location of the storage sites are shown in Figure 3 and key parameters are given in Table 2.

Table 2 Key data for the identified storage sites [17.]

Reservoir	**Utsira Formation**	**Gassum model area**	**Faludden storage unit**	**Havnsø trap**	**Gedser trap**
Formation	Utsira Fm	Gassum Fm	Faludden Fm	Gassum Fm	Bunter SS Fm
Location	Norway	Denmark	Sweden	Denmark	Denmark
Storage capacity (Mt)	21 300	3 700	745	926	245
Depth, top (m)*	450 – 1 500	1 000	830	1 500	850
Permeability (mD)	1 000	210	147	500	180

One of the cases involves utilizing the CO_2 for enhanced oil recovery (EOR) at the Gullfaks oilfield on the NCS. There are currently no CO_2-EOR projects ongoing in the North Sea, however, the technology is proven onshore in the U.S. Here, CO_2 injection for EOR purposes has been going on for decades using mostly naturally occurring CO_2. Assessing the potential for CO_2-EOR on the NCS is challenging due to the high uncertainties, especially regarding CO_2 volumes needed and the potential for increased oil recovery.

Reservoir modelling of North Sea oilfields was performed in [9.] The modelling resulted in a CO_2-EOR recovery rate of 4% of OOIP in a low recovery regime and 9% in a high recovery regime. IEA GHG [10.] adopted a recovery rate of 18% the for UK and Norwegian oilfields in their study. The CO_2 volumes estimated to be needed per barrel of incremental oil was in [11.] assumed to be 0.33 t. In a study of the UK sector of the North Sea, a minimum, maximum and a most likely value, 1.6, 2.6 and 1.8 bbl/t CO_2, respectively, were used [11.] And in the study by IEA GHG [10.], a ratio of 2.8 – 4.2 bbl/t CO_2 was assumed.

Reservoir properties, key numbers for the Gullfaks oilfield are given in Tables 3.

Table 3. Key numbers in million barrels for the Gullfaks oilfield [NPD,[13.]]

Gullfaks oil field	
Produced oil per 31.12.2014	2 248
Remaining oil reserves	100
Remaining resources at planned cessation according to approved plans	1 474
Original oil in place (OOIP)	3 822
Recovery rate as of 31.12.2014	59%
Expected recovery rate after planned cessation	61%

If we assume that 10% (which may be slightly on the optimistic side of what could be expected on the Norwegian Continental Shelf) of the original oil in place (OOIP) could potentially be recovered by applying CO_2-EOR and that 3.0 barrels of oil is produced for each ton CO_2 injected. The following potential oil production and total CO_2 volume injected over the project lifetime, and yearly injection rates assuming a lifetime of 15 years is given;

- 380 million barrels of oil
- 125 Mt of CO_2
- 8.3 Mt of CO_2 per year

A matter that complicates CO_2-EOR further is recycling of CO_2. The injected CO_2 will after sometime, (reservoir and injection regime dependent) be produced with the recovered oil. These CO_2 volumes are then recycled and injected back to the reservoir and thereby reducing the need for fresh CO_2. According to [15.], the U.S. experiences show that approximately 40% of the injected CO_2 can be expected to be produced with the oil. In [16.], where a CO_2 value chain on the NCS was considered, a CO_2 recycling rate of 75% (of CO_2 injected) was assumed.

Transport

For large-scale transport of CO_2, there are essentially two options, ship or pipeline. Both are proven technologies. Onshore transport of CO_2 in pipelines has been utilized in the U.S. for decades and offshore natural gas pipelines are common in the North Sea. Small-scale shipping of CO_2 for industrial use takes place today. Assuming offshore storage and/or EOR, the CO_2 infrastructure will also mainly be offshore, making both ship and pipelines relevant transportation methods. For large-scale transportation, the following conditions are being considered;

- Dense phase CO_2 in pipeline offshore
    - >80 barg, 25°C, <600 ppm_v H_2O
- Liquefied CO_2 on ship

  - 5.8 barg, –50˚C <50 ppm_v H_2O

In pipeline transport there will generally be a pressure loss over the length of the pipeline. There are two ways of assuring that CO_2 remains in a dense phase over the whole transport length; installation of booster stations along the pipeline route or providing a sufficiently high pressure at the inlet. The last option is adopted in this study as offshore booster stations will increase the complexity of the transport system.

Onshore transport in pipelines will be limited as the CO_2 emission sources selected for the CCS feasibility study almost exclusively are located on the coast. Onshore pipelines are however utilized as collection/feed pipelines to the main transport network. In addition, there are two cases studied where CO_2 transported is in its entirety onshore. According to [6.] the pressure limitation in such cases are 110 bar.

Transport networks are developed for the Nordic CCS cases based on the captured CO_2 volumes and the storage site locations. Transportation lengths are approximate numbers based on GIS (Geographical Information System). A distance factor has been added to the measured distance: 1.2 for onshore pipeline and 1.1 for offshore pipeline in order to account for terrain effects. No further considerations have been made with regard to terrain, nature conservation areas or topography along the selected pipeline route or basement conditions.

Economical

The assumptions that form the basis of the cost estimation of the CCS chain are provided in this chapter. Some assumptions are general and apply to capture, transport and storage, while others are relevant for a specific part of the CCS chain.

The following general assumptions apply:

- Cost in 2012[1]
- Rate of return: 7%
- No of years: 25 year
- Construction time: 1 year
- Capture cost (not avoided cost)
- Owners cost not included
- Detailed factor estimation method is used

Capture

The capture cost estimation is built up as cost for a generic MEA based post-combustion CO_2 capture plant, and adjusted with a location factor. The location factor is meant to reflect the effect location and type of industry would have on the costs. The details with regard to the location factor are

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[1] Project started in 2011.

provided at the end of this sub-chapter. The following assumptions apply to capture and in Appendix 1 the OPEX price list is provided.

- Nth of a kind. The first plant will be more expensive
- Generic cost level is based on Rotterdam conditions, with location factor 1.0
- Brown site (existing industrial area)
- Extension of the existing plant

Storage

It is challenging to estimate the cost of CO_2 storage mainly due to the large uncertainties. Consequently, the cost estimates provided here will be generic. No distinction will therefore be made between the identified storage sites. Consequently, it is important to keep in mind that these numbers are indicative only and final cost of CO_2 storage will only be known to the full extent when CO_2 storage is implemented at the specific sites. The storage costs will be site specific and depend on the CO_2 volumes to be injected, injection rate and storage capacity.

One of the major cost components is the drilling of wells, and the number of wells is highly dependent on the injection rates achieved on the individual site. The actual cost of drilling a well is not known and consequently it has not been possible to update previous cost data for storage. It was therefore decided to use the storage cost estimated in ZEP [8.] (Zero Emission Platform) for offshore storage in the North Sea, Skagerrak Basin and Baltic Sea and onshore storage in Denmark. Figure 4 shows the range of cost for different fields. The ranges are driven by setting field capacity, well injection rate and liability transfer cost to low, medium and high cost scenarios.

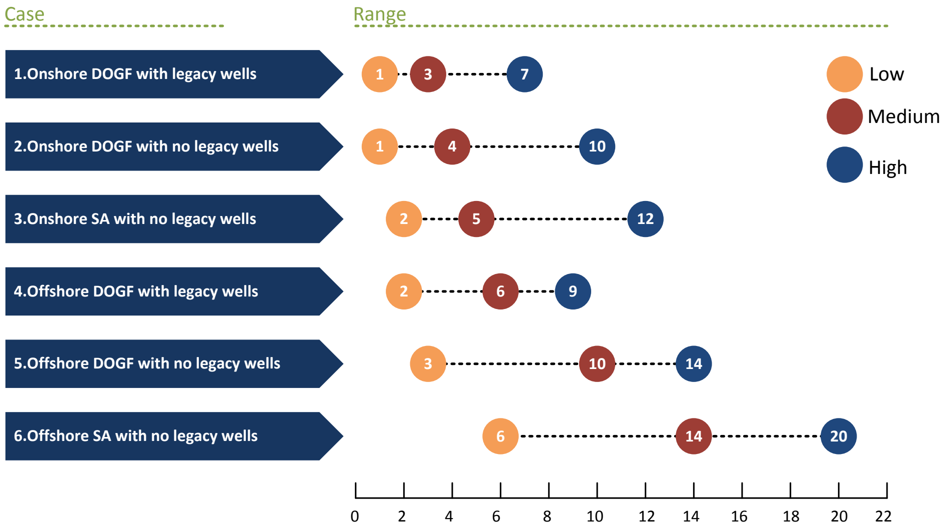

Figure 4 Storage cost (EUR/ton CO2 stored) with uncertainty range, ZEP report

For storage onshore in Iceland, the results from the CarbFix project have been used [7.]. These costs indicated the cost level, but it must be pointed out that the storage costs are very site specific and further investigation is needed.

Based on the knowledge of the formations and also the parameters for depth, permeability, etc. presented in table 2 and the storage cost presented in figure 4, these storage cost is assumed in this report:

- Utsira Fm: Offshore storage sandstone formations 7 EUR/t CO_2 [8.]
- Gassum Fm: Offshore storage sandstone formations 14 EUR/t CO_2 [8.]
- Faludden Fm: Offshore storage sandstone formations 16 EUR/t CO_2 [8.]
- Gedser and Havnsø trap: Offshore storage sandstone formations 20 EUR/t CO_2 [8.]
- Onshore storage basaltic rocks 13 EUR/t CO_2 [7.]

The storage cost is very site specific, and will vary with field capacity, number of wells needed (injectivity), onshore or offshore location and the complexity of the wells. Field capacity and injectivity have the largest effect on storage cost. It is therefore not very meaningful to estimate storage cost without this detailed information available.

There are also large uncertainties regarding the cost of CO_2-EOR. It was intended to provide cost estimates for CO_2-EOR at the Gullfaks oilfield, but this has been proven difficult to obtain. The net present value (NPV) of CO_2-EOR projects is strongly dependent on the input parameters, and oil price is one of the major factors. Over the past year, the oil price has dropped considerably[2]. Another important parameter is the project lifetime, CO_2-EOR projects are expected to have a considerably shorter lifetime than storage projects. A further complicating factor is the expected decline in fresh CO_2 volumes needed as the project progresses.

It has not been possible to develop cost scenarios for CO_2-EOR at Gullfaks. The approach chosen was instead to try and estimate what the value of CO_2 could potentially be in a CO_2-EOR project. The expected value of CO_2 differs depending on the stakeholder. A CO_2 emitter will want to sell the CO_2 to the oilfield operator, while the oilfield operator would probably like to receive the CO_2 for free or even against a fee. The deciding factor in regard to CO_2 value will ultimately be the economics of the CO_2-EOR project. As this is challenging to predict, two scenarios were foreseen. One where the CO_2 is valued 0 EUR/t, and one where the oil company receives the CO_2 against a fee, this fee is set equal to the storage cost at the Utsira Fm, which is 7 EUR/t.

Transport

Transport of CO_2 between the sources and sinks ties the CCS chain together. Beyond the transport itself, the pipelines and ships, the preparation for transport, potential hubs and the distribution of CO_2 streams between injection wells are included in the transportation costs. The CO_2 amount to be transported corresponds to 85 % of the emissions from the source. In some cases, the capture technology needs energy and steam, and the most economical solution is to include an energy plant to produce this energy. 85 % of the CO_2 from this source is included in the transport volume.

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[2] From well above \$100 in 2014 to below \$50 in 2015

Cost calculations for pipeline transport starts at 70 bar and 20°C at the site of the capture plant and ends at the storage site at a pressure of 70 bar and 0-20°C at sea level. Maximum onshore pipeline pressure has been set to 110 bar. Pressure in offshore pipelines has been set to 70 bar plus pressure drop depending on distance to the storage site. Offshore boosters have not been included in any of the systems. Adjustments to offshore pipeline thickness due to the pressure at the sea bottom have not been done.

For ship transport the following assumptions have been made: max ship size of 42 kt , transport conditions at 7 bar and minus 50°C, speed 15 knots and 4 hours for loading and unloading. Cost for liquefaction, intermediate storage (on barges with volumes corresponding to number of ships required for the transport), port fees and loading/unloading have been included.

Location factor

The location factor gives a value on conditions that might affect the capture cost at a plant at a specific location. It can be divided into two main areas due to:

- Due to type of industry
- Due to Location

The parameters included in the calculation of the location factor are;

- Industry types with :
  - Oil and gas offshore
  - Oil and gas refineries
- Area specifics
  - Number of qualified workers available
  - Travel and accommodation needed during construction
  - Waiting time for equipment and materials (bulks)
  - Construction equipment assignments
- Explosion (Ex) protection
  - Needed during construction, work permits and unexpected stops
  - Ex safe equipment needed
- Challenging climate conditions
  - Rain, snow and cold

The default generic factor is 1.00. Each site will be assessed in regard to the parameters listed above and be assigned a factor that will be added to the default generic factor. The final factor will be multiplied with the generic capture cost to find the local cost. The location factor matrix is given in Table 4

Table 4 Location factor matrix

Industry	Area specific	Ex	Ex during construction	Oil and gas	Challenging climate	Offshore
Refinery	0. – 0.20	0.05	0.2	0.15 – 0.20	0 – 0.25	-
Offshore	0.20	0.05	0.5	0.15	0 – 0.25	0.5
Heat and power	0. – 0.20	0.05	0.2	0 – 0.2	0 – 0.25	-
Cement	0. – 0.20	-	-	-	0 – 0.25	-
Chemicals	0. – 0.20	0.05	0.2	-	0 – 0.25	-
Non-ferrous metal production	0. – 0.20	-	-	-	0 – 0.25	-
Steel production	0. – 0.20	-	-	-	0 – 0.25	-
Pulp and paper	0. – 0.20	-	-	-	0 – 0.25	-

As can be seen from the table, the “specific area” factor, Ex (explosive area) factor and challenging climate factor equal for all the industries. If the industry have Ex under construction gives different values according to the plant descriptions and how much of the plant is influences by the Ex area. These factors are preliminary, and should be investigated in detail. In this project, the location factor has been included to illustrate the impact this factor can have on the capture cost.

NORDIC CCS CASES

In this chapter the Nordic CCS cases are described in more detail and the cost of the different elements of the CCS chain (capture, transport and storage) is estimated. The basis for the investigation is the CO_2 volumes and the technical and economic assumptions presented in the Assumptions chapter.

Case 1: Iceland

Case description

This case involves CO_2 emission sources on Iceland, and contains both onshore and offshore storage. Five sources have been identified; a power plant and four non-ferrous metal production plants. Four of these sources are located in relative close vicinity to each other on the west coast, while largest source, the larges, is located on the east coast. The location of the CO_2 emission sources are shown in Figure 5.

The main source in this case is the Hellisheiði geothermal heat and power plant. It is a small source with only 42 kt CO_2 emitted each year. However, they are in the forefront in regard to CO_2 (and SO_2)

capture on Iceland. For more information about the main source, see the NORDICCS report [5.]. In the vicinity of this geothermal plant there are three non-ferrous metal plants.

Two CCS cases are investigated;

- Case 1a CO_2 is collected from the four sources located on the west coast and transported in onshore pipelines to storage in basaltic rocks onshore near the Hellisheiði heat and power plant
- Case 1b CO_2 is collected from all four sources and transported by ship to the Utsira Fm in the North Sea

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Figure 5 CO_2 emission sources on Iceland

Capture cost

Capture cost for all the five sources has been calculated. In this estimation, capture with MEA is used, but the report [5.] investigated several other capture technologies that might be more suitable for CO_2 capture in combination with capture of SO_2. The cost level will vary with type of industry and location. Location factors are described in Section 4.4. A generic Capex and Opex for each site are estimated, and the location factor is added. Iceland is a special case when it comes to energy production/supply. There is a lot of geothermal energy that can be utilized. In these calculations, no additional cost for a CHP plant has been included for the industry sources. The estimated capture cost are presented in Table 5

Electricity cost and steam cost is lower in Iceland than in the other Nordic countries, so the price for both steam and electricity is reduced with 75 %.

Table 5 Capture cost, Case 1

Source	**CO_2 emission kt/yr**	**CAPEX generic, MEUR**	**OPEX generic, MEUR**	**Capture cost generic, EUR/t**	**Location factor**	**Capture cost local, EUR/t**
Elkem Iron steel	340	45	7	42	1.25	53
Hellisheiði Power and heat	40	12	2	83	1.25	104
Alcoa Fjardaàl Non-ferrous	520	250	31	130	1.25	163
Nordural Non ferrrous	420	210	25	135	1.25	167
Alcan Iceland Non-ferrous	280	140	17	140	1.25	172

The reason for the relative high capture cost for Hellisheiði plant is the small CO_2 volume. Two of the other sources are aluminium production plants with a CO_2 concentration of around 1 vol%, which increases the capture cost. Generally has Iceland small CO_2 volume from their industry, and thereby is the cost for capture CO_2 per ton high. The exception is Elkem, which has high CO_2 concentration in the flue gas.

Transport cost

The two cases studied have very different transport and storage solutions. One is a compact case, where CO_2 from four sources is transported to an onshore storage site (basaltic rocks) in close vicinity to the main source (Case 1a). The other case, Case 1b, involves all sources on Iceland, with onshore collection pipelines to a hub at Alcan. Here the CO_2 is loaded onto a ship for transport to the Utsira Fm of the coast of Norway via Alcoa located on the east coast of Iceland. Both cases are illustrated in Figure 6. In Table 6 the transport costs for the two cases are presented.

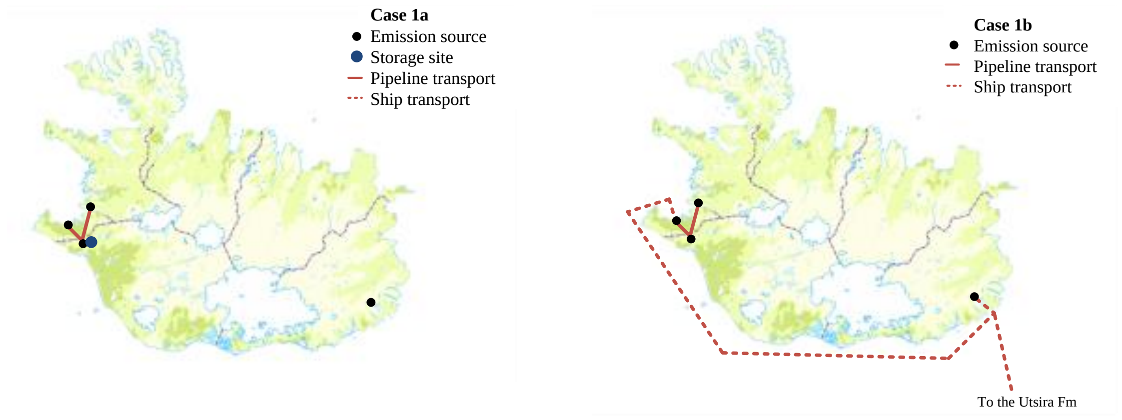

Figure 6 Transport alternatives, Case 1

Table 6 Transport cost, Case 1

Case	Transport mode	Facility	Capture Potential, kt/y*	Applied distance, km	CAPEX, MEUR	OPEX, MEUR	Transport cost, EUR/t CO_2
1a	Onshore pipeline	All sources (except Alcoa) to Hellisheiði	919	125	95	0.7	9.2
1b	Onshore pipeline/Ship	All sources to Utsira Fm	1 363	1 867	144	17	21.3

*Assuming 85% capture rate

Storage cost

As mentioned in the assumptions section of this report, there are large uncertainties when it comes to storage costs. The costs assumed for the two cases are;

- Case 1a – onshore storage basaltic rocks 13 EUR/t CO_2
- Case 1b – offshore storage Utsira Fm 7 EUR/t CO_2

Case analysis/conclusions

The Hellisheiði geothermal heat and power plant is the main source in this case. The CO_2 emissions from this plant alone are very small, but there is a possibility to store the CO_2 in basaltic rocks below the plant. Utilizing this storage site will reduce the transport cost considerably, and thereby reduce the total CCS cost for this plant. Nevertheless, the amount of CO_2 is small, so the CO_2 cost per ton is still relatively high.

The second option with storage in the Utsira Fm was included in the study due to the lack of alternatives to storage in basaltic rocks, in case of this proving to be difficult. The results from the

CarbFix project [7.] , however, are promising making the Utsira storage option even less likely. Onshore storage has so far met a lot of resistance in Europe; this may not be the case on Iceland. The public is general more familiar to gas and water stored underground, and this may be a viable solution for storage of CO_2 in the Iceland case.

The recommended case based on the above discussion is Case 2a. This results in a total CCS cost for the Hellisheiði plant is estimated to be in region of 130 EUR/t CO_2. For the other sources in this cluster, a cost of 9 EUR/t CO_2 needs to be added for the transportation, and also the capture cost varies from 53-172 EUR/t CO_2.

Case 2: Skagerrak

Case description

This case focuses on the Skagerrak Basin between Norway, Sweden and Denmark. It consists of CO_2 emission sources situated around this basin. The sources vary in types of industries; cement, refineries, and chemical. All of the sources are of considerable size, with emissions greater than 650 kt CO_2 per year. The location of the sources and their 2010 emissions are shown in Figure 7. In the figure, the number outside of the brackets is emissions due to fossil fuel, while the number inside the brackets denotes the total annual CO_2 emission. Here the biomass share is included. There are other sources in this region that could potentially be included in the case, but a choice was made to not do that at this time. The Norcem cement plant in Brevik, Norway is the main source in this case involving five cluster sources. The plant is owned by Heidelberg Cement and has an annual production of approximately 1.2 Mt of cement. The CO_2 emission at Norcem is partly due to the raw material (lime stone) and partly to burning of fuel. The majority of the fuel is coal, but an increasing amount of waste is utilized, of which a large fraction is biomass. This cement plant is also a driver for CCS in Norway, and has established a CO_2 capture test facility where several capture technologies is to be tested [20.] . For more information about the cement plant, please see the NORDICCS report [5.]

Four different CCS cases are investigated;

- Case 2a CO_2 is collected from all six sources, the CO_2 is transported for offshore storage in the Gassum Fm by a pipeline network both onshore and offshore
- Case 2b CO_2 is collected from all six sources and transported by pipeline to the Utsira Fm for offshore storage
- Case 2c CO_2 is collected from all six sources and transported by ship to the Utsira Fm for offshore storage
- Case 2d CO_2 is collected from all six sources and transported by pipeline to the Gullfaks oilfield for CO_2-EOR

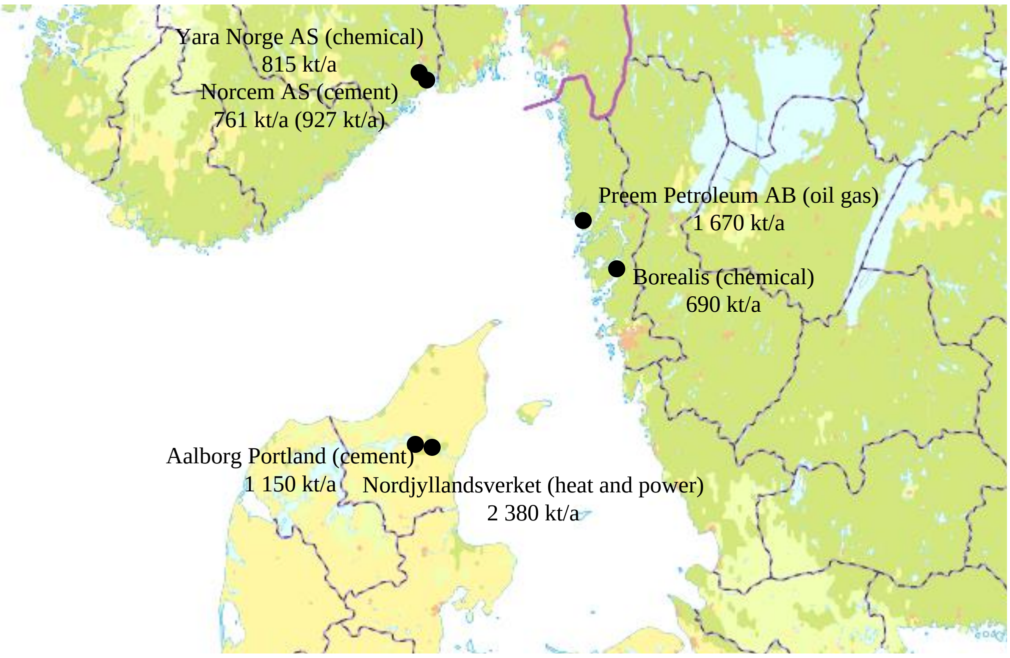

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Figure 7 CO_2 sources in Case 2

Capture cost

Table 7 shows the capture cost for the different sources, including Capex and Opex. The capture cost also includes a location factor. The location factor is described in the assumptions.

Table 7 Capture cost, Case 2

Source	CO_2 emission, kt/y	CAPEX generic, MEUR	OPEX generic, MEUR	Capture cost generic, EUR/t	Location factor	Capture cost local, EUR/t
Norcem, Brevik Cement	927	143	49	54	1.10	59
Yara Porsgrunn Chemical	815	135	43	60	1.10	66
Preemraff, Lysekil Refinery	1 670	257	86	58	1.48	86
Borealis Krackeranl., Stenungsund Chemical	690	172	48	69	1.13	78
Aalborg Portland, Nordjylland Cement	1 150	204	73	53	1.08	57
Nordjyllandsverket Heat and power	2380	245	108	63	1,98	68

In this case, there are large point sources, which is positive for the capture cost. The location factor differs from the industries and locations (see Table 4). The cement plants give the lowest cost for capture, and which is due to the high concentration of CO_2 in the flue gas and also high uptime.

Transport cost

Figure 8 shows the three selected transport routes, and indicates if it is ship or pipeline transport. Case 2a is pipeline transport to the Gassum Fm. Case 2b is a pipeline network to the Utsira Fm and Case 3c looks into ship transportation to the Utsira Fm from three hubs, one in each country. The hubs are located at the Norcem cement plant (Norway), at the refinery in Lysekil (Sweden), and at the coast in the northern part of Denmark. CO_2 is transported from the emission sources to the hubs via pipeline. Table 8 below gives the results of the transportation cost estimation for the different cases. All sources in the cluster are included in all transportation options.

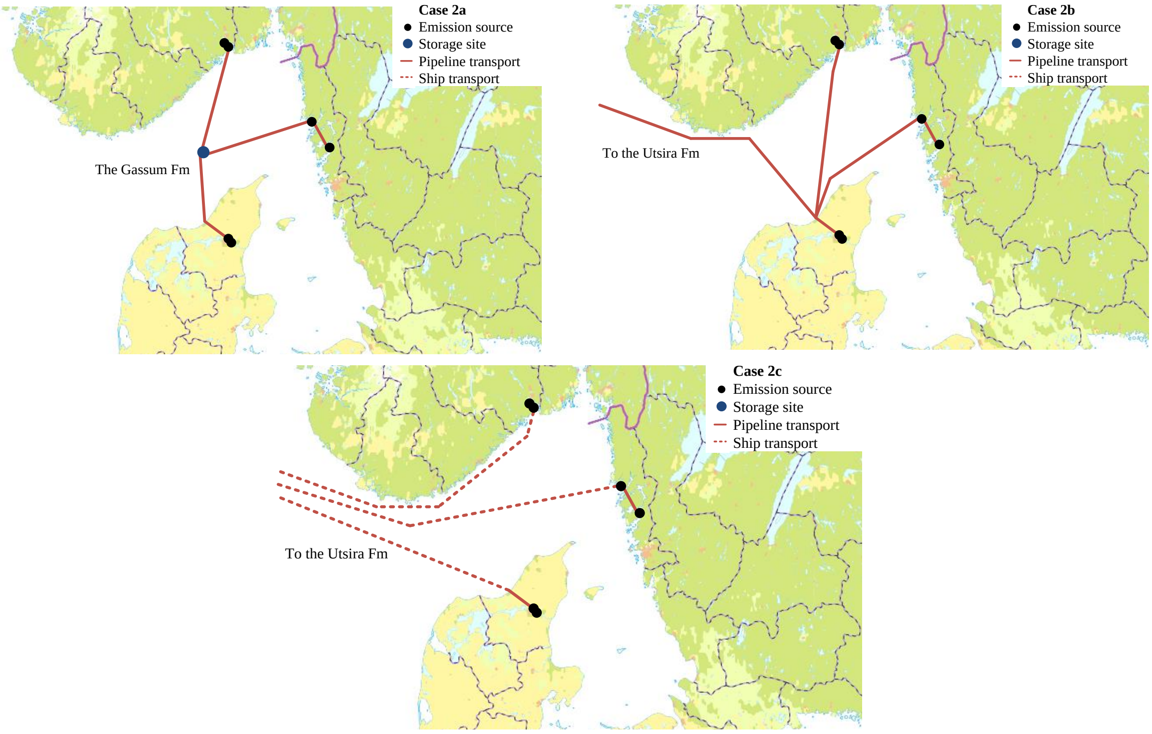

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Figure 8 Transport alternatives, Case 2

Table 8 Transport cost, Case 2

Case	Transport mode	Facility	Total CO_2 transported, kt/y	Applied distance, km	CAPEX, MEUR	OPEX, MEUR	Transport cost, EUR/t CO_2
2a	Pipeline Gassum Fm	All sources	9950	630	990	6	14.9
2b +2d	Pipeline Utsira Fm	All sources	9950	1 080	1 450	10	19.7
2c	Ship Utsira Fm	All sources	9950	1 275	830	105	15.3

Storage cost

As mentioned in the assumptions section, there are large uncertainties when it comes to storage costs. The costs assumed for the two storage sites are;

- Case 2a – offshore storage Gassum Fm 14 EUR/t CO_2
- Case 2b and 2c – offshore storage Utsira Fm 7 EUR/t CO_2

The difference in storage costs between the Gassum and Utsira Fms is mainly caused by higher uncertainties regarding the Gassum Fm. The Utsira Fm is a considerably larger storage site, with excellent injectivity. The potential injectivity in the Gassum Fm is currently assumed to be lower than for the Utsira Fm.

In the Assumptions chapter, a CO_2-EOR scenario where 125 Mt of CO_2 was needed over a 15 year period, with 8.3 Mt of CO_2 per year was suggested.

The total volume captured in this case is close to 10 Mt CO_2 and should therefore be sufficient to supply CO_2 to such a project. However, as the CO_2-EOR project progresses the amount of fresh CO_2 needed will decline as CO_2 produced with the oil will be recycled for reinjection into the oilfield. Two cost scenarios are foreseen; 0 and 7 EUR/t CO_2.

Case analysis/conclusions

This case has been thoroughly studied in previous projects [21.] as it has some advantages when it comes to CO_2 capture and storage. There are several large emitters within a relatively small geographical area, the sources are close to sea, and with a potential storage site nearby. All of these factors facilitates for a case where the CCS costs could potentially be low. Disadvantages might be that there will be cross border transport, different operational time etc.

The results show that large sources give lower capture cost per ton CO_2, and that distance has a major impact on the transport cost, especially for the pipeline. The Gassum Fm is the nearest storage site. However less information is available on this site compared to the Utsira Fm and this is reflected in the storage costs. The difference in storage costs between the two formations is such that it might cover the cost of transporting the CO_2 for a longer distance. In this case, the low storage cost in the Utsira Fm, compensates for the longer transport route compared with storage in the Gassum Fm.

Ship and pipeline transportation give different cost pictures; pipelines have high capital cost, and lower operational cost. For ship it is the opposite. An extra benefit for ship is the possibility to reuse ships in other CO_2 projects or for LNG transport.

Even if there are challenges when several sources are to cooperate, there is also likely to be benefits, by sharing the cost for storage and to a lesser extent, transport. In addition, CO_2 for EOR demands large and stable amounts of CO_2. Therefore, it is probably necessary to include at least more than one sources of CO_2 in an EOR project.

Case 3 Finland, the Bay of Bothnia

Case description

Along the coast in the Bay of Bothnia there are a number of relatively large CO_2 emitters, there are however no storage sites identified in the proximity. The sources are predominantly iron and steel, and pulp and paper. A generic steel plant situated close to the Metsä-Botnia plant near Tornio, Finland is chosen as the main source. Figure 9 gives an overview of the sources selected for this case study which makes up this large, but compact cluster. The emission numbers reported in the figure are for almost all of the emitters divided into two, one outside of brackets and one inside the brackets. The number outside of the brackets is emissions due to fossil fuel, while the number inside the brackets denotes the total annual CO_2 emission. Here the biomass share is included. For the pulp and paper plants it can be observed that the bio based CO_2 emissions are considerably higher compared to their fossil based emissions. The bio based CO_2 emissions are included in this study.

Four CCS cases are investigated;

- Case 3a CO_2 is collected from all eleven sources, the CO_2 is transported for offshore storage in the Faludden Fm by a pipeline network both onshore and offshore
- Case 3b CO_2 is collected from all eleven sources and transported by pipeline to the Faludden Fm for offshore storage
- Case 3c CO_2 is collected from all eleven sources and transported by ship to the Utsira Fm for offshore storage
- Case 3d CO_2 is collected from all eleven sources and transported by onshore pipeline to a hub at Melkøya for storage in the Barents Sea

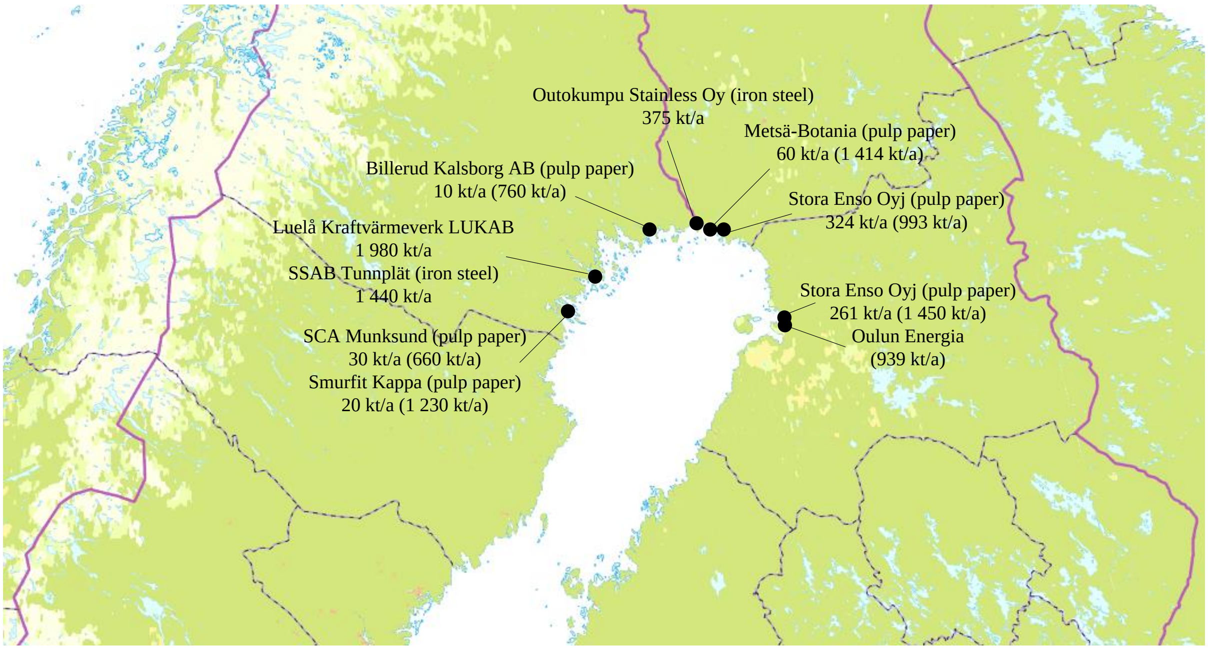

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Figure 9 CO_2 sources in Case 3.

Capture cost

The estimated capture costs for the identified CO_2 emission sources are presented in Table 9. The capture technology used is post-combustion with MEA for all cases. It is likely that there is potential for optimizing the CO_2 capture and thus reduce the cost of capture. Such a detailed analysis is not a part of the current report. For more information regarding options for capture, see the NORDICCS report [5.].

The emissions have a wide range, from 375 kt per year to almost 3 Mt per year. The sources are mainly pulp and paper plants with some iron and steel plants. The location factor is described in the chapter "Assumptions", and as can be seen from Table 4, this factor is the same for all emission sources. The reason for this is that all of the sources lie in the same geographical region and that the type of emission sources does not warrant any special considerations.

Table 9 Capture cost Case 3

Source	CO_2 emission, kt/y	CAPEX generic, MEUR	OPEX generic, MEUR	Capture cost generic, EUR/ton	Location factor	Capture cost local, EUR
GSP (Generic steel plant), Finland Iron steel	2 854	438	153	60	1.35	81
SCA Munksund, Sweden Pulp and paper	660	117	35	62	1.35	83
Smurfit Kappa, Sweden Pulp and paper	1230	198	63	59	1.35	80
SSAB Tunnplätt , Sweden Iron steel	1440	238	78	61	1.35	82
LUKAB, Sweden Heat and power	1980	167	84	58	1.35	78
Billerud Karlsborg AB, Sweden Pulp and paper	760	135	42	62	1.35	84
Outokumpu Stainless Oy, Finland Iron steel	375	79	22	68	1.35	91
Metsä-Botania, Finland Pulp and paper	1 414	239	77	60	1.35	81
Stora Enso Oyj (1) Finland Pulp and paper	1 450	242	79	60	1.35	81
Stora Enso Oyj (2) Finland Pulp and paper	993	172	55	61	1.35	82
Oulun Energia Heat and power	939	89	41	60	1.35	81

This cluster consists over several large CO_2 emitters, and it can be seen from the estimated capture costs that there are only small differences. The most noticeable, being that the smallest source has the highest costs as expected. The generic capture cost is generally low, due to the high CO_2 emission levels, but the addition of the location factor increases the costs and reflects the somewhat remote location.

Transport cost

As there are no local storage options, the transport distance could potentially be long. In Figure 10, the selected transport options for Case 3 are shown. Case 3a consists of onshore and offshore collection pipelines that feed CO_2 from the CO_2 sources to a central pipeline. In Case 3b and c (not shown) the CO_2 is transported by onshore pipeline to four hubs and then transported by ships to storage, the Faludden and the Utsira Fm, respectively.

Onshore pipeline can be interesting for short distances, but transport over land to Melkøya/Barents Sea provides a number of issues other than costs. Both natural preservation areas and undulated landscape will make this option challenging. It is at this point considered more likely that the CO_2 will be transported by sea to the Faludden Fm and even the Utsira Fm. The Melkøya/Barents Sea option is not considered further in the current report, the reader is referred to the NORDICCS report D20 "Recommendation on transport solutions". In this report the possibility of transporting CO_2 in onshore pipelines between Bothnia Bay and Brent Sea/North Sea was investigated. The conclusion was that this is not likely to be a valid option as the pipeline has to pass regions with sensitive nature (e.g. Natura 2000[3]) and involve several crossings of lakes and/or rivers and also mountains.

A challenge for ship transport in Bothnia Bay is that severe icing conditions during the winter months are likely, potentially making icebreakers necessary. This possibility has been partially accounted for through the application of a 10% offshore terrain factor for the ship transport in this area.

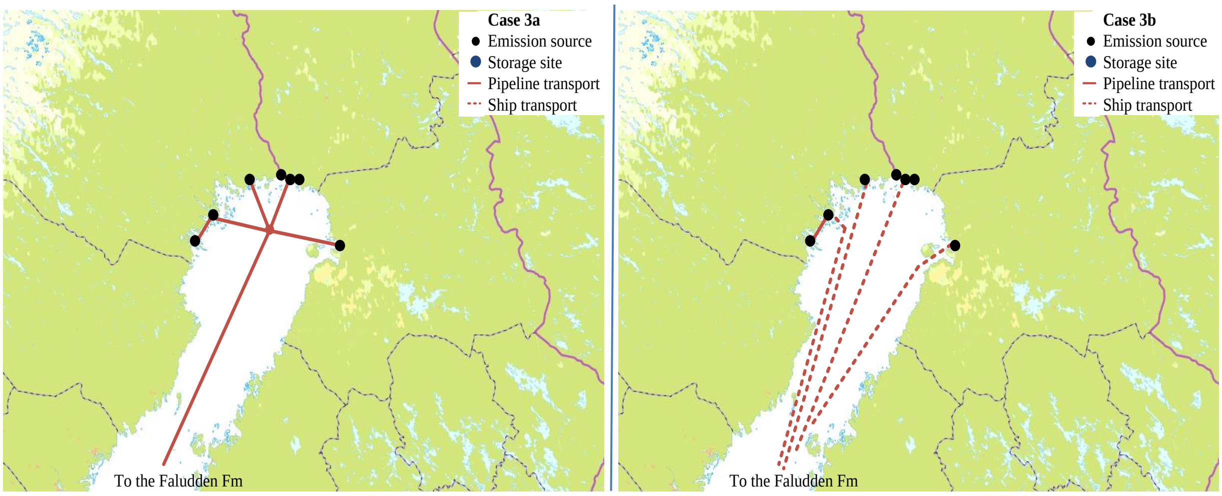

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Figure 10 Transport alternatives for Case 3

Table 10 Transport cost, Case 3

	Main Transport mode	Facility	Capture potential, kt/y	Applied distance, Km	CAPEX, MEUR	OPEX, MEUR	Transport cost, EUR/ton CO_2
3a	Pipeline Faludden Fm	All sources	14 095	1 724	3 752	18	21.4
3b	Ship transport Faludden Fm	All sources	14 095	2587	1 298	159	18.3
3c	Ship transport Utsira Fm	All sources	14 095	4475	1 346	182	20.9

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[3] Natura 2000 is an EU-wide network of nature protection areas established under the 1992 Habitats Directive.

As can be seen in the table above, ship transport to Faludden Fm gives the lowest transport cost per ton CO_2. The estimated transportation costs are similar for all three cases, with the pipeline option being slightly more costly. The difference between ship transport to Faludden and Utsira is small, with the Utsira case being slightly more expensive. The reason for this small difference even though the transport distance to Utsira is considerable longer is that the main cost for the ship is the pre-treatment and also the on- and off-loading. The travel distance has less impact on ship transport cost compared with pipelines, where the transport distance is very important.

Storage cost

The Faludden Fm is the nearest storage site for this cluster. It might be that the injection capacity at Faludden is not enough for all the sources nearby. The lack of storage options nearby will affect the total CCS costs as the transportation costs might increase. As mentioned in the assumptions chapter, there are large uncertainties when it comes to storage costs. The costs are assumed to be;

- Case 3a, b and c – offshore storage at Faludden Fm is assumed to be 16 EUR/t CO_2 and storage in the Utsira Fm is assumed to be 7 EUR/t CO_2.

The difference in costs are due to the lack of information about the Faludden Fm. Compared to the Utsira Fm it has a significantly smaller storage capacity and the injection rate is expected to be lower (i.e. more injection wells is likely needed)

Case analysis/conclusions

This is a large cluster with a considerable amount of CO_2, but it is also located relatively far away from storage sites. This is challenging for the transport network. The cluster benefits are not that prominent due to the currently available ship size and long transport distances. An optimization regarding the number of sources might reduce the costs. The ship solution (Case 3b) gives longer transportation distances, but it is still less expensive than pipeline per ton CO_2. The cost of storage is lower at Utsira compared to storage in Faludden Fm. Even though the cost for transportation is lower to Faludden, the storage cost influence the CCS cost in such a way that the total CCS chain is cost optimized with transport to the Utsira Fm.

Case 4: North east coast of Sweden

Case description

This case consists of a number of sources both in Sweden and Finland, with the majority of the CO_2 emitters located on the Swedish side. All of the sources on the Swedish side are pulp and paper plants with biomass as the main fuel. The identified sources are shown in Figure 11, the number outside of the brackets is emissions due to fossil fuel, while the number inside the brackets denotes the total annual CO_2 emission. Here the biomass share is included. The cluster is elongated and covers a large area on both sides of the Baltic Sea. The main source is the pulp and paper plant SCA Östrand. This source mainly emits CO_2 originating from biomass, and this poses challenges in regard to CCS. Biogenic CO_2 is considered to be neutral and capture of this CO_2 is not likely to take place without incentives. Currently there are no economic incentives for implementing CCS on these types of sources and there is no regulation for reducing biogenic CO_2. Still, biogenic CO_2 comprises a major part of the CO_2 emissions, and it could be that incentives for capturing biogenic CO_2 could be in place in the future.

Two CCS cases are investigated;

- Case 4a CO_2 is collected from all ten sources, the CO_2 is transported for offshore storage in the Faludden Fm by a pipeline network both onshore and offshore
- Case 4b CO_2 is collected from all ten sources and transported by ship to the Faludden Fm for offshore storage

The storage site of choice is the Faludden Fm (as it is for Case 3). The CO_2 storage capacity at this site is likely to be limited, and therefore the Utsira Fm should also be considered due to the relatively large volume of CO_2. Pipeline transport is estimated using onshore collection pipelines between the sources with spines from selected sources (hubs) to a connection point in the Bay of Bothnia where a large pipeline transports the whole CO_2 volume to the Faludden Fm.

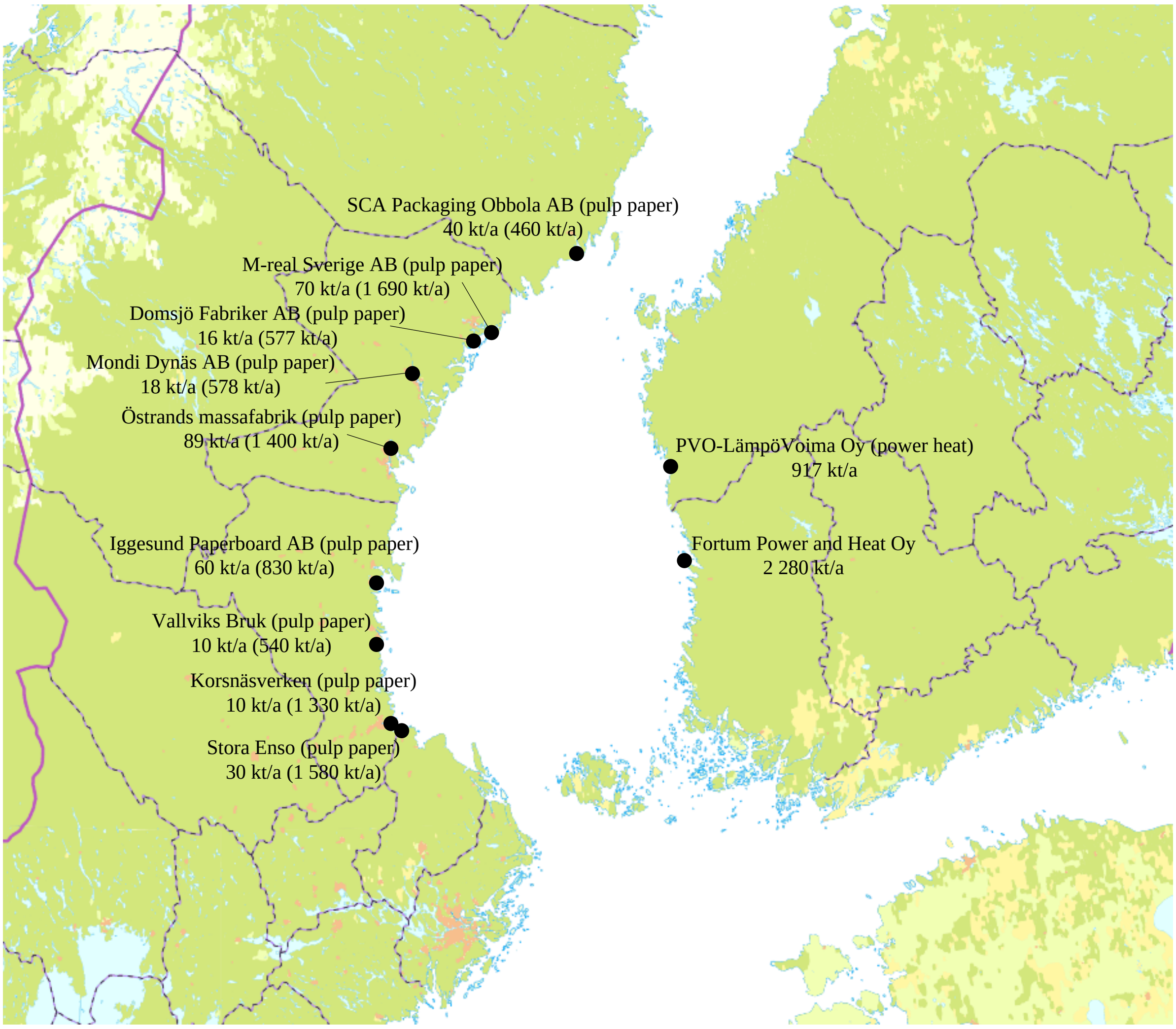

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Figure 11 CO_2 sources in Case 4.

Capture cost

Post-combustion MEA is the assumed capture technology for all emission sources. All but two sources are pulp and paper producers with no complicating factors due to the production. Therefore, the location factor is due to the geographic location alone. The two heat and power plants have higher location factors, due to ex. areas and also higher influence of the remote area. The main source, SCA Östrand, has been investigated with regard to capture technology in the NORDICCS report [5.]. The estimated capture costs are presented in Table 11.

Table 11 Capture cost Case 4

Source	**CO_2 emission, kt/y**	**CAPEX generic, MEUR**	**OPEX generic, MEUR**	**Capture cost generic, EUR/t**	**Location factor**	**Capture cost local, EUR/t**
SCA packing Obbola Pulp and paper	460	90	26	64	1.2	76
M-real Sverige Pulp and paper	1 690	271	90	59	1.2	70
Domsjö Fabriker Pulp and paper	577	106	32	62	1.2	74
Mondi Dynäs Pulp and paper	578	106	32	62	1.2	75
Östrand massfabrikk Pulp and paper	1 400	230	75	59	1.2	71
Iggesund Paperboard Pulp and paper	830	141	45	60	1.2	72
Vallisvik bruk Pulp and paper	540	102	30	62	1.2	75
Kosnäsverken Pulp and paper	1 330	213	71	59	1.2	71
Stora Enso Pulp and paper	1 580	253	85	59	1.2	70
PVO-Lämpö Oy power and heat	917	122	48	66	1.6	105
Fortum P&H Oy power and heat	2 280	235	103	63	1.6	100

The NORDICCS report [5.] considers possibilities for bio-energy with CCS (BECCS) as pulp mills mainly have biogenic CO_2 emissions. This work investigated the potential of implementing carbon capture to pulp mills using a conventional recovery boiler or black liquor gasification (BLG) technology. The latter scenario using either the Selexol process together with a combined cycle for electricity production or the Rectisol process together with biofuel production proved favourable from a CO_2 capture perspective. The results show that the pulp and paper industry is suitable for BECCS. The combination of BLG technology and CO_2 capture would require low additional utility, compared with the conventional post-combustion process. Three different post-combustion capture technologies are compared and the results are presented in Table 12.

Table 12. Comparison between the capture technologies.

Technology	CAPEX, kEUR	OPEX, kEUR/y	Net reduction, CO_2, t/y
Selexol	64 100	15 420	318 000
MEA	64 970	30 880	715 000
Rectisol	93 080	12 030	393 000

The capture technology using MEA resulted in a high utility consumption, especially regarding steam and cooling water. However, the overall balance showed that when producing the required steam, additional electricity was generated. Consequently more electricity could be sold and this reduced the cost of CO_2 capture. The operational cost for Selexol and Rectisol is lower, but the net reduction of CO_2 per year is higher for MEA. Based on these conclusions, it seems that MEA is the least costly process option. This might be different with different assumptions, and should be investigated further.

Transport cost

The two investigated transport options are illustrated in Figure 12. Case 4a consists of onshore and offshore collection pipelines, with a main offshore pipeline to the Faludden Fm. In Case 4b, onshore collection pipelines are used to transport the CO_2 to three hubs. The CO_2 is then transported to the Faludden Fm by three dedicated ships. In Table 13, the estimated transport costs are presented.

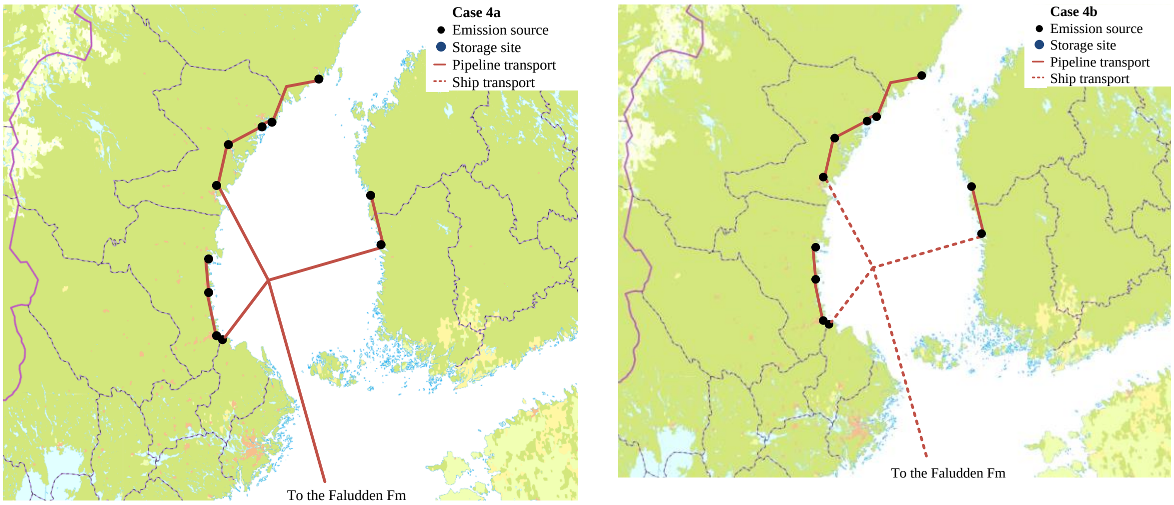

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Figure 12 Transport alternatives for Case 4.

Table 13 Transport cost for Case 4.

Case	Transport mode	Facility	Capture Potential, kt/y	Applied distance, km	CAPEX, MEUR	OPEX, MEUR	Transport cost, EUR/ton CO_2
4a	Pipeline Faludden Fm	All sources	14 806	1 577	2 288	14,1	12,6
4b	Ship transport Faludden Fm	All sources	14 806	1 851	1 453	106	14,6

Storage cost

As described earlier in the report, the storage cost has high uncertainty. It is assumed in this report that the CO_2 storage cost for storage in the Faludden Fm is 16 EUR/t and storage in Utisra Fm is 7 EUR/t.

Case analysis/conclusions

The cluster in this case is large, with almost 15 Mt of CO_2 annually. Such a cluster provides both opportunities and challenges when it comes to transport and storage. Pipeline transport is more cost efficient for larger volumes over shorter distances. However, such amounts could provide a challenge for storage as there might be limitations on storage capacity and injectivity in the Faludden Fm. If the storage capacity limit is reached, the alternative is likely to be storage in the Utsira Fm. Ship transport solutions could provide the flexibility needed in this type of scenario, as the economic risks will be reduced.

Case 5: Copenhagen

Case description

This case is defined as one source to sink, with a short distances to storage. The CO_2 emission source is Amagerværket, a combined heat and power plant located in Copenhagen, Denmark. The plant emits close to 2 Mt of CO_2 annually, the location of the plant is shown in Figure 13. This plant utilizes both biomass and coal as fuel, and has relatively large CO_2 emissions. In the figure, the number outside of the brackets is emissions due to fossil fuel, while the number inside the brackets denotes the total annual CO_2 emission. Here the biomass share is included.

Three CCS cases are investigated;

- Case 5a CO_2 is collected from the source, the CO_2 is transported for offshore storage in the Gedser Fm by an offshore pipeline
- Case 5b CO_2 is collected from the source, the CO_2 is transported for offshore storage in the Gedser Fm by a ship
- Case 5c CO_2 is collected from the source, the CO_2 is transported for onshore storage in the Havnsø Fm by an onshore pipeline

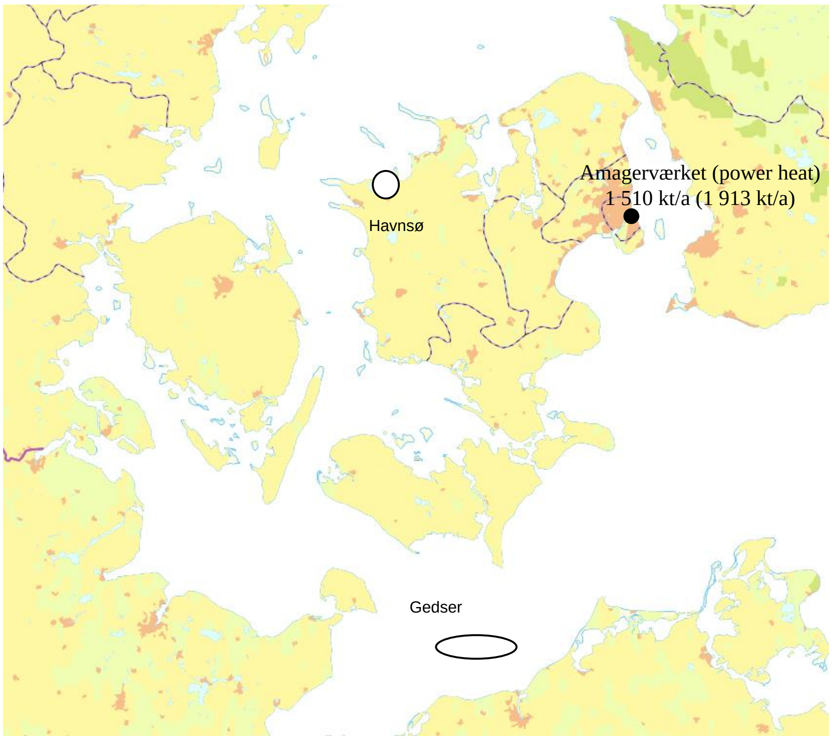

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Figure 13 Amagerværket in Case 5.

The reservoirs south in Denmark are small, and little developed. According to the work performed in work package 6 in the NORDICCS project there are several storage sites that might be suitable for CO_2 storage in this region. In this case, the Havnsø Fm and the Gedser trap are considered as storage sites for the captured CO_2 from Amagerværket.

Capture cost

The estimated CO_2 capture cost using post-combustion MEA is presented in Table 14. The location factor is low, only slightly above the reference value of 1. The reason for this is that no complications are expected due to type of plant and that the plant is located in a densely populated geographic region with a relatively mild climate.

Table 14 Capture cost Case 5.

Source	Total CO_2, kt/y	CAPEX generic, MEUR	OPEX generic , MEUR	Capture cost generic, EUR/t	Location factor	Capture cost local, EUR/t
Amagerværket Heat and power	1 510	167	67	65	1.05	68

Transport cost

Three different pipeline and ship options have been evaluated, with two different storage options. These are shown in Figure 14 and the results are presented in Table 15.

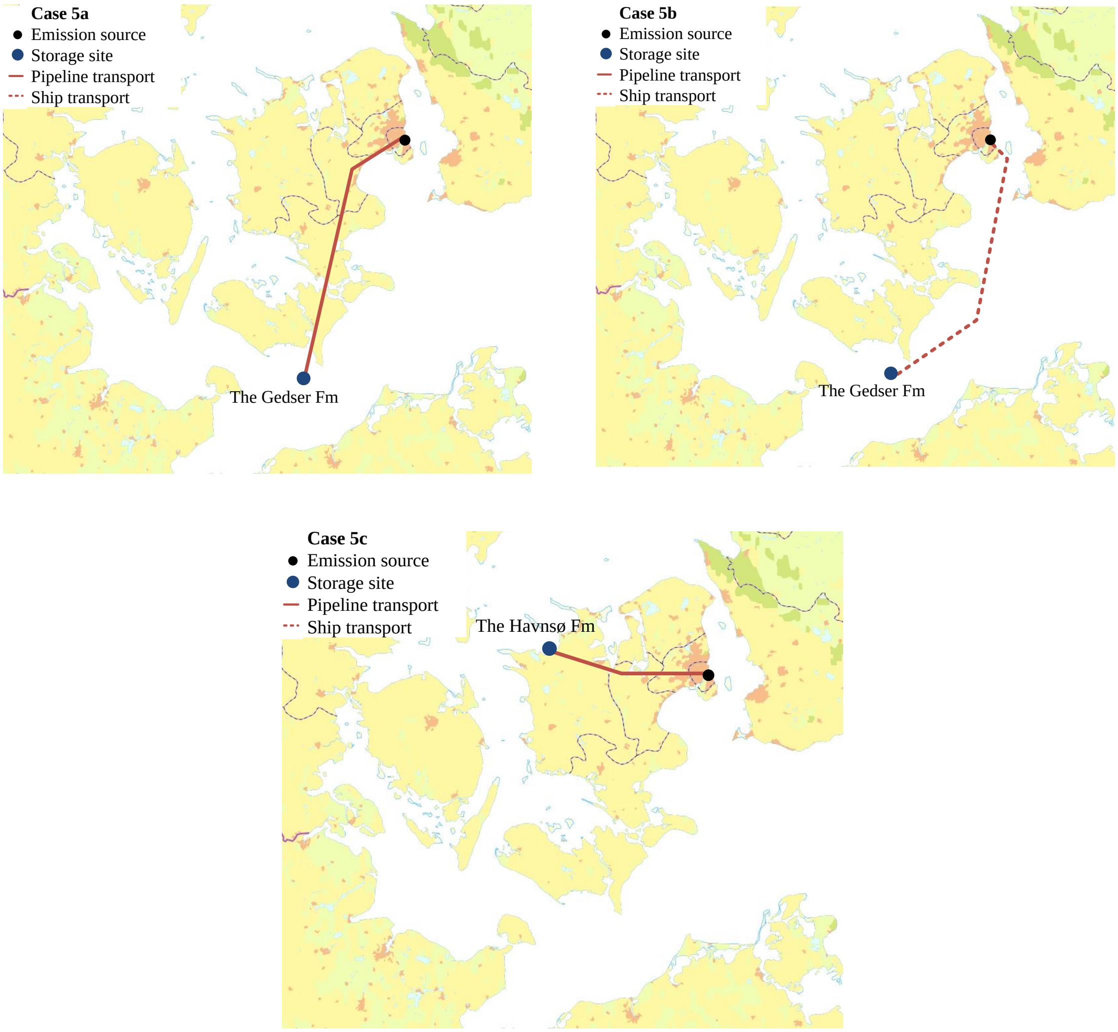

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Figure 14 Transportation alternatives in Case 5.

Table 15 Transport cost, Case 5

Case	Transport mode	Storage place	Facility	Capture Potential, kt/y	Applied distance, km	CAPEX, MEUR	OPEX, MEUR	Transport cost, EUR/t CO_2
5a	Pipeline offshore	Gedser	Amagerværket	1510	180	226	1.65	13.6
5b	Ship transport	Gedser	Amagerværket	1510	175	95	12	13.1
5c	Pipeline onshore	Havnsø	Amagerværket	1510	90	77	0.5	4.6

Storage

The two storage sites in Denmark are located close to shore. This makes the transportation shorter, and the weather conditions will not affect the injection which could potentially be an issue in the North Sea. The Havnsø trap is one of the most promising storage sites in Denmark, with high permeability and no major faults cutting through the structure. The lack of new high quality data is a general issue for all Danish sites; both wells and seismic surveys are often old, due to the fact that there is no hydrocarbon exploration in these areas since the beginning of the 1970es.[17.]

The storage cost is very hard to obtain; little information regarding the traps raises the uncertainties and thereby the costs. In this estimation, the higher level of cost for such a site is used, and the cost is assumed to be 20 €/t CO_2. More information regarding these fields is needed, and if the uncertainties of injectivity, permeability and storage potential are reduced, the cost for storage of CO_2 may also be reduced.

Case analysis/conclusions

Several transport options have been evaluated, and the lowest transport cost is found for storing CO_2 in the Havnsø Fm due to the short onshore transport distance. For the Gedser case, due to the volume and short distance, there is a break even for the ship and pipeline transport cost per ton CO_2 transported. But as can be seen, the investment cost is much higher for the pipeline, so if risk is an important matter, ship transport is recommended. But there are additional parameters that might be taken into account. There are several large CO_2 emitters in Denmark (many of them based on biomass), and if the volume increases, the pipeline options is likely to be preferable when it comes to costs. Another important aspect is that there has been some public resistance to onshore storage in Denmark. Public acceptance is important for any CCS chain and could ultimately be the deciding factor.

Case 6: Lysekil

Case description

This case consists of sources that lie relatively close to each other and within the same country, Sweden. The main source in this cluster is the Preem refinery located at Lysekil, south west of Sweden. This refinery is relatively large with an annual capacity of refining 11.4 Mt crude oil and other oil feedstock. Refineries are usually complex plants depending on the number of refining steps included. The Preem refinery has a total of 8 chimneys (stacks), which could pose a challenge when it comes to CO_2 capture. This cluster consists of several CO_2 sources along the west coast of Sweden. The cluster is relatively compact with a moderate CO_2 volume. In addition, it is a national cluster unlike the Skagerrak cluster (Case 2). In Figure 15 the location of the sources are shown. In the figure, the number outside of the brackets is emissions due to fossil fuel, while the number inside the brackets denotes the total annual CO_2 emission. Here the biomass share is included.
Three CCS cases are investigated;

- In Case 6a CO_2 is collected from all of the sources, the CO_2 is transported for offshore storage in the Gassum Fm by an offshore pipeline
- In Case 6b is CO_2 is collected from all of the sources, the CO_2 is transported for offshore storage in the Gassum Fm by a ship
- In Case 6c is CO_2 collected from all of the sources, the CO_2 is transported for offshore storage in the Gassum Fm by ships and pipelines. This is a combination of Case 6a and 6b.

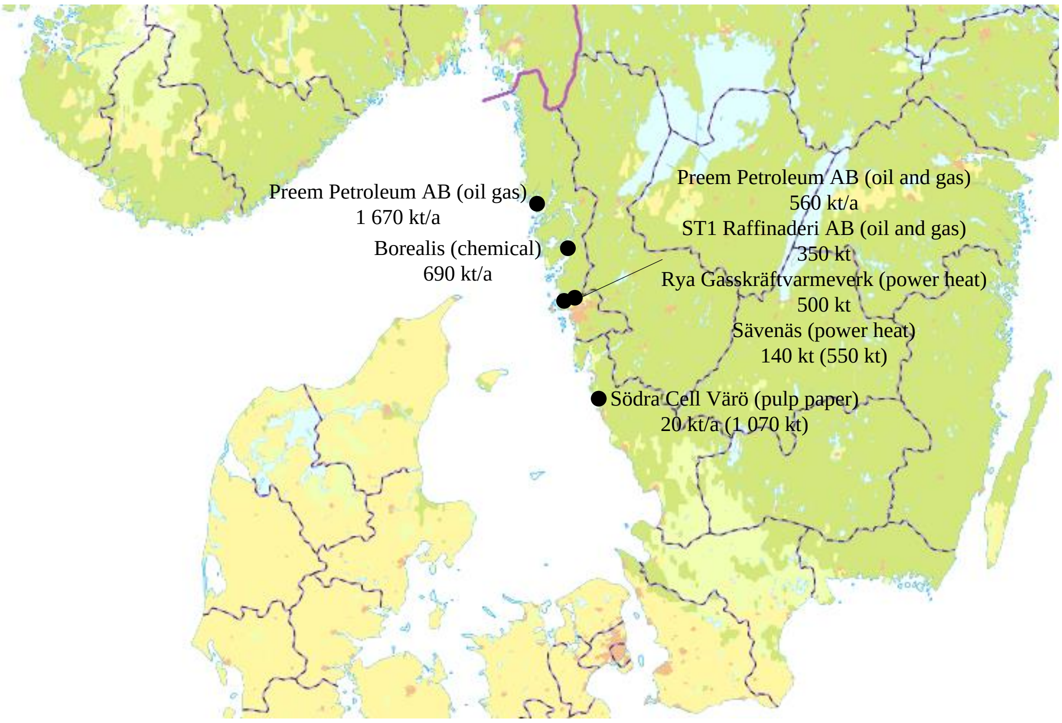

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Figure 15 CO_2 sources in Case 6.

Capture cost

The capture cost is estimated based on MEA capture technology.The capture costs for the identified sources are provided in Table 16. The location factor is relatively high for the chemical plant and the refineries. The geographical location does not warrant any specific considerations as this is a densely populated region with no specific challenges in climate.

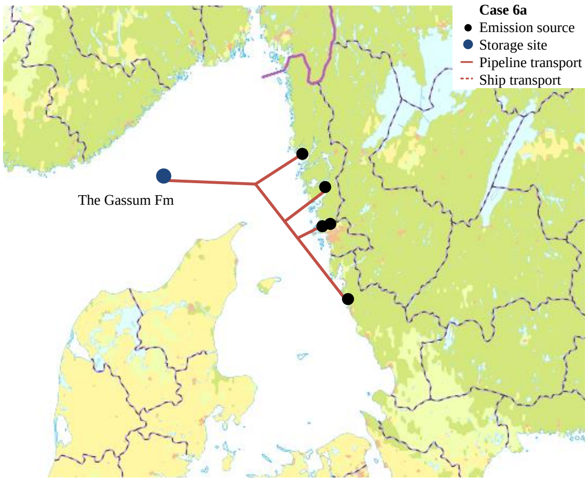
Table 16 Capture cost Case 6.

Source	**Total CO_2, kt/y**	**CAPEX Generic, MEUR**	**OPEX generic, MEUR**	**Capture cost generic, EUR/t**	**Location Factor**	**Capture cost local, EUR/t**
Borealis ethylene cracker, Stenungsund Chemical	690	157	42	72	1.39	100
Preemraff, Lysekil Refinery	1 670	254	86	58	1.54	89
Preem Petroleum AB Refinery	560	125	41	61	1.54	94
ST1 refineryi*, Gothenburg Refinery	350	73	19	67	1.54	103
Rya, Gothenborg Power and heat	500	139	29	101	1.39	140
Södra cell, Varø Pulp and paper	1 070	169	54	59	1.14	68
Sävensäs, Renova Heat and power	550	78	26	72	1.39	100

*Shell refinery in Gothenburg was sold to ST1 in 2010

Transport Cost

Case 6a describes a solution where all transport is by pipeline, onshore (short distances) and offshore. Case 6b gives a transport solution where 3 of the sources each have a dedicated ship to storage. The four sources located in Gothenburg, are transported onshore in pipelines to a hub, and then further transported with ship to storage. Case 6a and c are illustrated in figure 16.



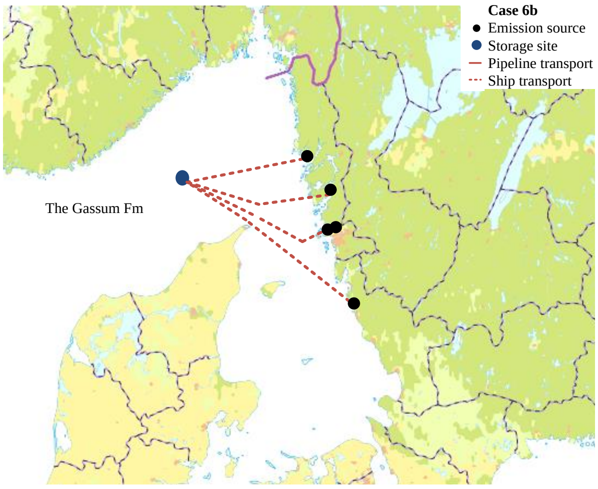


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Figure 16 Transport alternatives for Case 6.

The total transportation distance is relatively short when considering number of sources included in the case. The amount of CO_2 is moderate, and the storage site is located nearby, and all these influence the transport costs. The same amount of CO_2 is transported to the same storage site, the Gassum Fm, for the three cases. Case 6a is all pipeline transport and Case 6b is ship transport from 4 sites, both include some onshore pipeline transport of the CO_2 to the nearest hub. Case 6c is a combination of Case 6a and b; 2 sites transported with ship, and 2 offshore pipelines. The cost estimation results are given in Table 17.

Table 17 Transport cost, Case 6

Case	**Transport mode**	**Facility**	**Transport volume, kt/y**	**Applied distance, km**	**CAPEX, MEUR**	**OPEX, MEUR**	**Transport cost, EUR/t CO_2**
6a	Pipeline Gassum	All sources	7754	540	1 128	4.6	13.8
6b	Ship Gassum	All sources	7754	860	630	61	15.3
6c	2 sites with ship and 5 sites with pipelines	All sources	7754	940	775	20	11.7

The results from Case 6a and b show that pipeline transport is more cost efficient than ship transport for this case. A closer look at these two cases gave rise to a third possible transport option, a combination of ship and pipeline. Ship transport from Södra cell and Borealis (see figure 15) and pipeline transport from Preem refinery in Lysekil and from the sources in the Gothenburg area.

Storage

Storage site in this case is Gassum Fm. This formation is rather close to the sources, and has a large storage potential. The costs assumed for the Gassum offshore storage is 14 EUR/t CO_2. This formation is in an area with little oil and gas activity, and there is a need for more investigation regarding the storage potential and injectivity for this storage site.

Case analysis/conclusions

The total volume of CO_2 is moderate, however, when taking into account the relatively short distance between the sources the cases still show an acceptable cost level. Capture cost varies by amount of CO_2. The ST1 (previously Shell) refinery has low volumes of CO_2, which results in an increased cost per ton CO_2 relative to the other sources. However, its location close to other sources may contribute to making it economically viable in a CCS perspective.

Case sensitivity and optimization

When considering CO_2 capture from an industrial site, one capture plant is foreseen located on the site. However, depending on the size of the area covered by the plant and the number of process gas emission points a distributed MEA based capture plant (more than one absorber and one common desorber) could be an option. The major advantage for this configuration is the shortened transport distance for the process gas. Process gas vents/channels are voluminous and relatively costly. However, the savings made are for the most part evened out by additional construction materials needed for the added absorbers and the longer transport distance for rich and lean amine circulated between the distributed absorbers and the single. The Preem refinery at Lysekil has 5 large stacks, and these are placed in a large and elongated area. This report has investigated the possibility of having 5 absorbers and one common desorber at a site. This configuration is then compared to the standard configuration with one absorber and one desorber, the results are given in Table 18.

Table 18. Absorbers and desorber configurations.

Configuration	CAPEX, MEUR	OPEX, MEUR	Capture cost, EUR/t
1 absorber, 1 desorber	251	85.5	58
5 absorbers, 1 desorber	256	83.5	61

The results show that there are benefits for this solution, but the assumptions and site specific conditions will influence if this is a cost saving possibility. The solution was not more cost efficient than the common desorber and absorber configuration. With the current assumptions, there are no economic benefits with several absorbers. The distance between the absorbers and the desorber was estimated to be 300 m. This distance influences the costs and a shorter distance could improve the cost picture. A detailed analysis of the option with several absorbers and common desorber is described in [19.]. Here, different absorber/desorber configurations were studied for an aluminium production plant. The results were similar to the ones found in the table above and it was concluded that such small differences in the costs provides flexibility to the capture plant layout. This could be beneficial for plants with limited area available for a CO_2 capture plant.

OVERALL CONCLUSIONS

This report 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 that influence the cost estimation results, and this makes it difficult to draw any general conclusions. 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.

Transport and storage are necessary parts of the CCS chain, but the capture cost is the dominating cost element. The cost of capture is mostly dependent on the CO_2 volume. The generic capture cost, with the current assumptions, and primarily lies in the region of 55-90 EUR per ton. This wide cost distribution is mainly due to the variation in CO_2 volume and to some extent CO_2 concentration of the flue gas. Inclusion of the location factor increase the capture cost to varying degree, depending on type of industry and on the geographic region (climate and population density) in which the plant is located. The adjustment of the generic cost with the location factor gives a more realistic cost estimate for the specific CO_2 emission sources. This could then indication as to which type of industries and geographical regions where CO_2 capture could be more cost efficient. Industries that typically increase the complexity are refineries and chemical plants. The geographical region that seems to be the most challenging is the Bay of Bothnia.

The transport costs depend on the CO_2 volumes and the transport distance, and generally lie in the region of 12-20 EUR per ton. For most cases it was found that ship based transport network was the least costly solution, however, there are exceptions, most notably Case 5 (Denmark) and Case 1 (Iceland). In addition, it was found that some cases would benefit from having a transport network comprising both ship and pipeline. Such an optimization proved beneficial for Case 6, where the transport costs were reduced when both ship and pipeline was used. This result is likely due to the short distance to storage. Transport over long distances favours ship over pipeline. The operational cost is higher for ship, but the sunk cost in pipelines is considerable and reduces the flexibility of the transport network. Flexibility of transport is likely to be needed as there are large uncertainties when it comes to the timeframe of implementation of CCS on individual plants and 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.

Storage costs have been proven hard to obtain, and a complicating factor is that the cost is very site specific. Reliable cost estimates for storage can only come from increased knowledge of the specific storage reservoir. Still, an effort was made to combine storage costs provided by ZEP and the storage sites identified in the NORDICCS project. The furthest developed and well known storage site is the Utsira Fm, which is therefore given the lowest cost. The other storage sites were, due to lack of information, given costs higher than Utsira. 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 Fm was considered for storage, it was found that even though another storage site was located closer, storage at Utsira was the most cost optimal solution for the chain. The reason for this is because the 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 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 also politically, and is therefore not a straight forward solution. The Faludden Fm is not expected to be able to store all the CO_2 from the Bay of Bothnia. It is therefore likely that the CO_2 from this region would need to be transported to the Gassum Fm or even further, to the Utsira Fm.

It is clear from the results reported on CCS costs that there is need for cost reductions in all parts of the CCS chain. The capture cost is the dominating element and optimization in capture technologies is needed. Designing a transport network for a cluster is challenging mainly due to the likely stepwise and unpredictable implementation of CO_2 capture. Further investigation into ship and pipeline network combinations is recommended. Increased knowledge on the storage sites is necessary. Storage capacity and injectivity are key parameters when estimating the storage costs. If the storage cost for the identified sites in the Nordic region could be reduced down to the cost level of Utsira, then not only the storage cost would be reduced, but potentially also the transport costs.

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ABBREVIATIONS

BECCS – Bio-Energy with Carbon Capture and Storage
CAPEX – Capital Expenditure
EOR – Enhanced Oil Recovery
OPEX – Operational Expenditure
ZEP – Zero Emissions Platform

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Appendix 1

Cost information

Operational cost price list used in the calculations

Table 19 . OPEX price list

Reservoir parameter	Unit	Unit cost (EUR/unit)
Electric power	kW	0.1
Electric power in Iceland	kW	0,025
Natural gas	Sm^3	0,25
Steam	NOK/ton	170
Steam in Iceland	NOK/ton	45
Town water	m^3	0.0125
Cooling water	m^3	0.00255
MEA replacement	kg	1,8
Na_2CO_3	kg	0,575
Active coal	Kg	5,5
Corrosion inhibitor	Kg	1,875
MEA waste handling	Kg	0,25
Operator/engineer	Hours	50
Maintenance	% of CAPEX/year	4

Operational time and CO_2 content assumptions for the industry plants

Table 20. Industry sources

Source	**type of industry**	**Operational time (h/y)**	**CO_2 content %**
Norcem	cement	8322	22 %
Yara	Chemical	8322	10 %
Preem petroelum AB	Refinery	8322	10 %
Borealis, Stenungsund	Chemical	8322	5 %
Aalborg Portland	Cement	8322	22 %
Nordjyllandsverket	Heat and power	8000	12%
Elkem	Steel	8585	22 %
Hellisheiði	Heat and power	7600	69 %
Alcoa Fjardal	Al prod	8760	1 %
Nordural	Al prod	8760	1 %
Alcan Iceland	Al prod	8760	1 %
SCA Munksund	pulp and paper	8000	10 %
Smurfit Kappa	pulp and paper	8000	10 %
SSAB Tunnplätt	steel	8000	22 %
Luleå kraftvarmeverk	heat	7600	12 %
Billerud Karlsborg AB	pulp and paper	8000	10 %
Outokumpu Stainless Oy	steel	8000	22 %
Metsä-Botania	pulp and paper	8000	10 %
GSP, Botnia bay	Steel	8000	28 %
Stora Enso Oyj (1) (Oulun)	pulp and paper	8000	10 %
Stora Enso Oyj (2)	pulp and paper	8000	10 %
Oulun Energia	Heat	7600	12 %
SCA packing Obbola	pulp and paper	8000	10 %
M-real Sverige	pulp and paper	8000	10 %
Domsjö Fabriker	pulp and paper	8000	10 %
Mondi Dynäs	pulp and paper	8000	10 %
Östrand massfabrikk	pulp and paper	8000	10 %
Iggesund Paperboard	pulp and paper	8000	10 %
Vallisvik bruk	pulp and paper	8000	10 %
Kosnäsverken	pulp and paper	8000	10 %
Stora Enso	pulp and paper	8000	10 %
PVO-Lämpö Oy	heat	7600	12 %
Fortum P&H Oy	heat	7600	12 %
Amagerværket	heat and power	8000	12 %
Borealis Krackeranl.	Chemical	8322	5 %
Preem petroleum AB	refinery	8322	10 %
ST1 refinery	refinery	8322	10 %

Rya , Gotenborg	heat and power	5500	4 %
Södra cell Varø	Pulp and paper	8585	10 %
Sävensäs, Renova	Heat	8000	10 %