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# Carbon Capture and Storage (CCS) in industry sectors – focus on Nordic countries

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**Abstract**

Six CCS cluster cases specific to the Nordics countries have been identified based. The technical and economical aspect related to capture and transportation for these cases have been investigated. As this is an ongoing study the results are preliminary and storage is yet to be assessed, only the storage location is known. The end goal of the project is to assess the feasibility of the identified CCS cases based on the final technical and economical evaluation. The industries targeted in this study are oil and gas, cement, iron and steel, pulp and paper and heat and power. The industrial cases that have been investigated in this assessment involve all the Nordic countries and cover a wide variation of $CO_2$ volume, distance between sources, number of sources and distance to storage. The capture costs, with the current assumptions, generally lie in the region of 40-50 EUR/ton and are mainly dependent on the size of the $CO_2$ emission source. The transportation costs depend strongly on the $CO_2$ volumes and the transportation distance, and were estimated to approximately 17-20 EUR/ton. Ship transportation seems to be the least expensive transportation method, however there are exceptions.


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*Keywords:* CCS, $CO_2$ emissions, Nordic countries, clusters

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## 1. Introduction

NORDICCS is a virtual CCS networking platform aiming at boosting the deployment and commercialization of CCS technology in the Nordic region. The project involves some of the major CCS stakeholders representing industry, academia and research organizations in the five Nordic countries. The NORDICCS project is funded by Nordic Innovation together with the project partners and was launched in 2011. The first project period ends in 2015 and plans are currently made to continue also after the funding period. The overall aim is to develop a Nordic CCS roadmap defining a vision for industrial CCS implementation in the Nordic countries. The roadmap will outline the technologies and industries most attractive for $CO_2$ capture, transport and storage in the Nordic countries in addition to providing a timeline for their implementation.

In this work a selected number of CCS cases specific to the Nordic region have been identified and studied in more detail. Technical and economic aspects related to $CO_2$ capture and transport has been studied. Current results are preliminary. It should be noted that storage is yet to be assessed, and only the storage location is currently known. The goal of the project is to assess the feasibility of the identified CCS cases based on the final technical and economical evaluation done in NORDICCS.

**Nomenclature**

| | |
|---|---|
| CCS | Carbon capture and storage |
| CAPEX | Capital expenditure |
| EOR | Enhanced oil recovery |
| Hub | A connection point for $CO_2$, intermediate storage and terminal for further transportation |
| LNG | Liquefied natural gas |
| MEA | Monoethanolamine |
| OPEX | Operational expenditure |

## 2. Methodology

### *2.1. Case development*

Nordic emission sources exceeding 100 000 t $CO_2$/yr have been identified and reported [1]. These sources also include $CO_2$ emissions originating from biogenic sources. No distinction has been made in this study between fossil and biogenic $CO_2$ emissions.

The case studies in this study assess capture, transport and storage possibilities in the Nordic region. Emission sources from all the Nordic countries are represented and the sources chosen reflect the industries which are relevant for the region.

Six cases were identified and studied:

- Iceland
- Skagerrak
- Bay of Bothnia
- Sweden and Finland
- Copenhagen
- Lysekil

Fig. 1 shows the emission sources and storage sites used in the case studies. The case study on power production in Iceland is presented in Section 3.1. The case studies have been developed around a main source for which a detailed study on $CO_2$ capture was performed. Emission sources nearby are included to form a cluster for $CO_2$ transport and storage.


Fig. 1. Selected $CO_2$ sources and storage sites in the Nordic Countries.

### *2.2. Assumptions*

Several assumptions had to be made prior to cost estimation. The cost estimation is based on the NORDICCS work on the CCS roadmap for the Nordic countries [2]. All $CO_2$ capture is based on post-combustion MEA technology with a capture rate of 85%. Industrial operation hours are assumed to be 8 000 h/yr. Transportation costs include all cost up to the injection site. Consequently, distribution of $CO_2$ streams between storage wells have been added to the transportation cost. Distance factors of 1.2 for onshore pipeline and 1.1 for offshore pipeline have been added. Storage costs are yet to be calculated. The maximum ship load is 42 000 tons, transportation at 7 bar and minus 50°C, speed 15 knots, 4 hours for loading and unloading. Cost for liquefaction, intermediate storage (1x the size of the ship), port fees and loading/unloading were included. Cost has been calculated using the net present value method in Euros for 2012 exchange rate, discount rate has been set to 8 % over 25 years (2 years construction, 23 years of operation).

## 3. NORDIC CCS Case studies

### *3.1. Case 1: Iceland*

Iceland is located approximately 1 450 km from the west coast of Norway. Five $CO_2$ emission sources have been identified. These include a geothermal power plant, an aluminum production plant and iron production plants.

The Hellisheiði geothermal power plant is operated by Reykjavik Energy and has a capacity of 330 MW electricity and 133 MW thermal energy. The $CO_2$ emissions from the geothermal processes are low, less than 50 000 t $CO_2$/yr. This type of power plant is typical for Iceland and offers a unique possibility to store captured $CO_2$ in basaltic rocks beneath the plant.

Fig. 2 illustrates the selected sources and the storage site as well as possible transportation options. In Case 1a pipeline transportation to basaltic rock at Hellisheiði has been assessed and in alternative 1b a combination of pipeline and ship to the Utsira formation in the North Sea has been assessed.

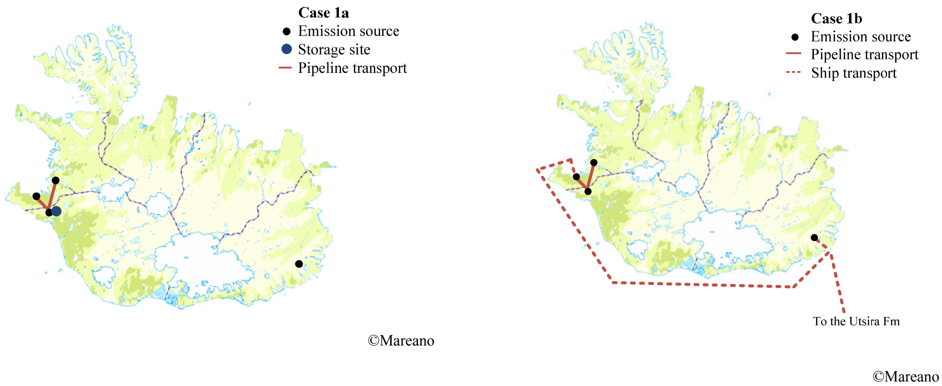


Fig. 2. Identified transportation alternatives for Case 1.

Table 1 and 2 shows capture and transportation costs for alternatives 1a and 1b.

Table 1. Capture cost, Case 1.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (kEUR) |
|---|---|---|---|---|
| Elkem, Iceland | 342 | 91 000 | 12 300 | 59.3 |
| Hellisheiði, Iceland | 42 | 34 200 | 2 900 | 117.1 |
| Alcoa Fjardaàl, Iceland | 523 | 138 200 | 24 000 | 68.9 |
| Nordural, Iceland | 419 | 122 200 | 19 800 | 72.6 |
| Alcan Iceland, Iceland | 278 | 96 300 | 13 900 | 80.3 |

Table 2. Transportation cost, Case 1.

| Case | Transportation mode | Facility | Capture Potential (kt/yr)* | Applied distance, km | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 1a | Pipeline | All sources (except Alcoa) | 919 | 125 | 95 000 | 700 | 8.6 |
| 1b | Pipe/Ship Utsira | All sources | 1 363 | 1 867 | 398 000 | 30 300 | 44.3 |

Utilizing the basaltic rocks beneath the geothermal power plant will reduce the transportation cost to almost nothing, thereby reducing the total cost for this $CO_2$ source. Nevertheless, the amount of $CO_2$ is small, resulting in a high capture cost per ton $CO_2$. Iceland does not have many emitters of $CO_2$, with the Alcoa Aluminum plant with approximately 523 000 t $CO_2$/yr as the largest.

Onshore storage has so far been met with a lot of resistance in Europe i.e. Germany and Denmark. This seems to not be the case on Iceland so far, but continued information to the public is necessary.

### *3.2. Case 2: Skagerrak*

Skagerrak is the sea basin located between the southern part of Norway, the western Sweden and northern Denmark. The main source in this case study is the Norcem Heidelberg Cement plant in Brevik, Norway. The assessed cluster includes five additional $CO_2$ emission sources located in Norway, Sweden and Denmark. The Gassum formation, located in the Skagerrak Basin just off the coast of northern Denmark is one possible offshore storage site. Assessment of storage in the Utsira formation was also included. $CO_2$ transportation using both ship and pipeline was studied. Fig. 3 illustrates the three selected transportation alternatives. Case 2a is a network of pipelines to the Gassum formation. Case 2b is a pipeline network to the Utsira formation and Case 2c is a combination of ship and pipeline transportation to the Utsira formation.

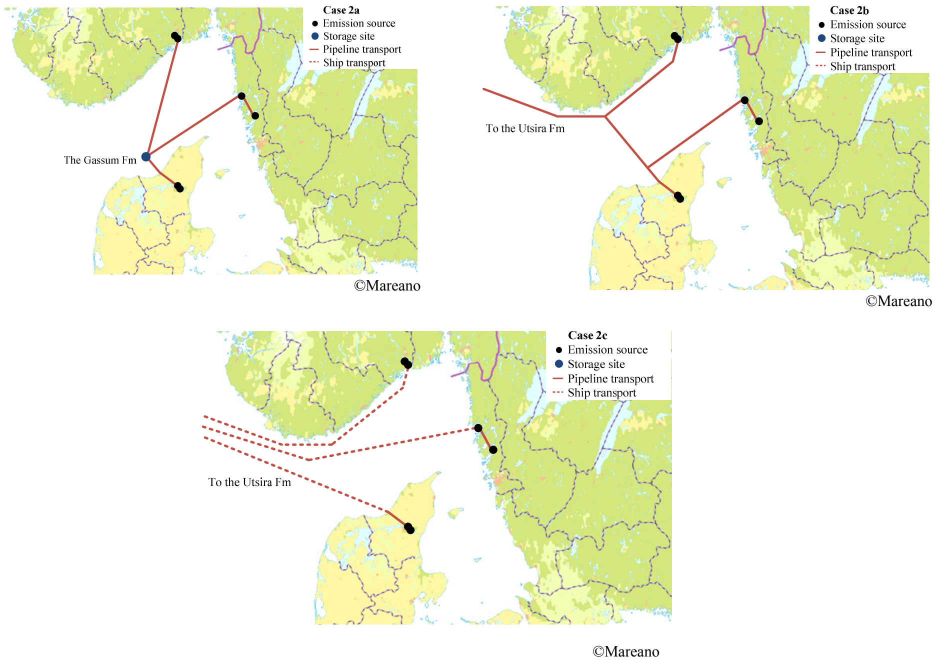


Fig. 3. Identified transportation alternatives for Case 2.

Table 3 and 4 shows the capture cost and transportation costs for Case 2.

Table 3. Capture costs, Case 2.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (EUR/ton $CO_2$) |
|---|---|---|---|---|
| Norcem, Brevik, Norway | 927 | 121 300 | 27 500 | 46.8 |
| Yara Porsgrunn, Norway | 815 | 156 000 | 26 500 | 49.3 |
| Preem Petroleum, Lysekil, Sweden | 1 670 | 295 400 | 57 100 | 49.6 |
| Borealis Krackeranl., Stenungsund, Sweden | 690 | 104 500 | 23 200 | 53.4 |
| Aalborg Portland, Nordjylland, Denmark | 1 150 | 190 300 | 43 900 | 40.3 |

| | | | | |
|---|---|---|---|---|
| Nordjyllandsværket, Nordjylland, Denmark | 2 380 | 274 900 | 73 800 | 41.1 |

Table 4. Transportation costs, Case 2.

| Case | Transportation mode | Facility | Capture Potential (kt/yr) | Applied distance (km) | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 2a | Pipeline Gassum | All sources | 6 785 | 626 | 990 000 | 6 000 | 14.9 |
| 2b | Pipeline Utsira | All sources | 6 785 | 1073 | 1 450 000 | 10 000 | 19.7 |
| 2c | Ship Utsira | All sources | 6 785 | 1 274 | 830 000 | 105 000 | 15.3 |

The table shows that large emission sources have a lower cost per ton $CO_2$. It also shows that distance has a major impact on the transportation cost. Ship and pipeline cost gives 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. It can be seen from the tables that large sources give lower cost per ton $CO_2$, and distance has a major impact on the transportation cost.

### *3.3. Case 3: Bay of Bothnia*

There are several large $CO_2$ emitters situated around the Bay of Bothnia. 11 sources in Sweden and Finland were selected for this case study. It was estimated that a total of 14 Mt $CO_2$ could potentially be captured from the selected sources. The Faludden formation located in the southern part of the Baltic Sea is a potential storage site for this case study. Two transportation alternatives have been studied. Alternative 3a is a pipeline transportation network where the $CO_2$ is transported from the sources to a connection point for a joint pipeline to the Faludden formation. In alternative 3b $CO_2$ is capture from the selected sources and transported to intermediate storage hubs through onshore pipelines. From the hubs the $CO_2$ is transported by ship to the Faludden formation.

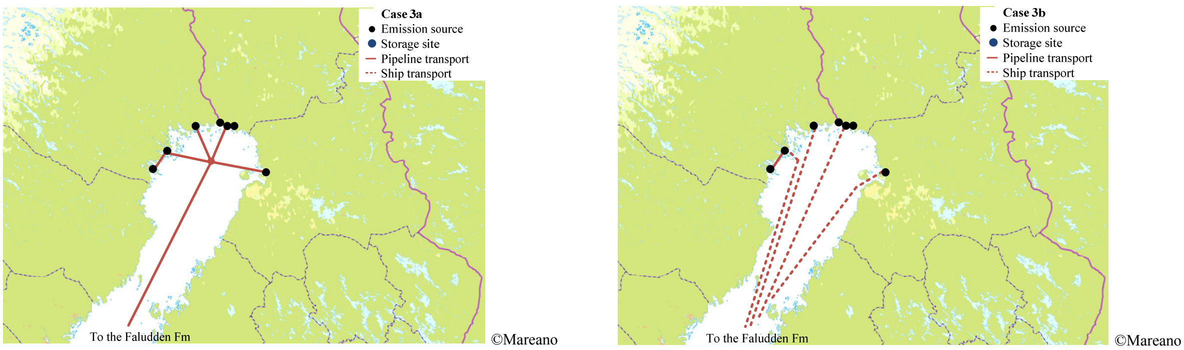


Fig. 4 Identified transportation alternatives for Case 3.

Table 5 and 6 shows the capture and transportation costs for Case 3.

Table 5. Capture cost, Case 3.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (EUR/ton $CO_2$) |
|---|---|---|---|---|
| GSP (Generic steel plant), Finland | 2 854 | 257 500 | 98 800 | 43.1 |
| SCA Munksund, Sweden | 660 | 150 200 | 28 800 | 50.4 |
| Smurfit Kappa, Sweden | 1 230 | 194 200 | 41 200 | 47.3 |
| SSAB Tunnplätt, Sweden | 1 440 | 207 800 | 41 900 | 42.5 |
| LUKAB, Sweden | 1 980 | 275 800 | 63 500 | 44.3 |
| Billerud Karlsborg AB, Sweden | 760 | 163 400 | 32 500 | 49.3 |
| Outokumpu Stainless Oy, Finland | 375 | 337 100 | 95 400 | 49.0 |
| Metsä-Botania, Finland | 1 414 | 232 500 | 47 700 | 48.1 |
| Stora Enso Oyj (1) (Oulu), Finland | 1 450 | 236 400 | 48 800 | 47.9 |
| Stora Enso Oyj (2), Finland | 993 | 222 600 | 44 700 | 48.7 |
| Oulun Energia, Finland | 939 | 190 000 | 32 700 | 52.5 |

Table 6. Transportation cost, Case 3.

| Case | Transportation mode | Facility | Capture Potential (kt/yr) | Applied distance (km) | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 3a | Pipeline Faludden | All sources | 14 095 | 1 724 | 3 752 000 | 18 000 | 21.4 |
| 3b | Ship transport Faludden | All sources | 14 095 | 4 475 | 1 298 000 | 159 000 | 18.3 |

Case 3 is a large cluster with considerable $CO_2$ emissions. However, there are no storage sites in this region and this increases the cost of transportation. The capture cost is mainly affected by the amount of $CO_2$ and the location factor, and to a lesser degree the $CO_2$ concentration. The transportation cost is mainly affected by the amount of $CO_2$ and distance to storage. Four ship routes in alternative 3b increase the transportation distance for this solution. Still it is less expensive than pipeline transportation per ton $CO_2$.

### *3.4. Case 4: Sweden and Finland*

This case is based on a number of emission sources on the east coast of Sweden and the west coast of Finland. The total $CO_2$ capture potential from these sources is close to 11 Mt. Fig. 5 shows that the cluster is elongated covering a large area and that it has a shorter transportation distance to the Faludden formation compared to Case 3. The main source is the pulp and paper plant SCA Östrand in Sweden, emitting approx. 1 400 kt $CO_2$/yr., and emits mainly biogenic $CO_2$.

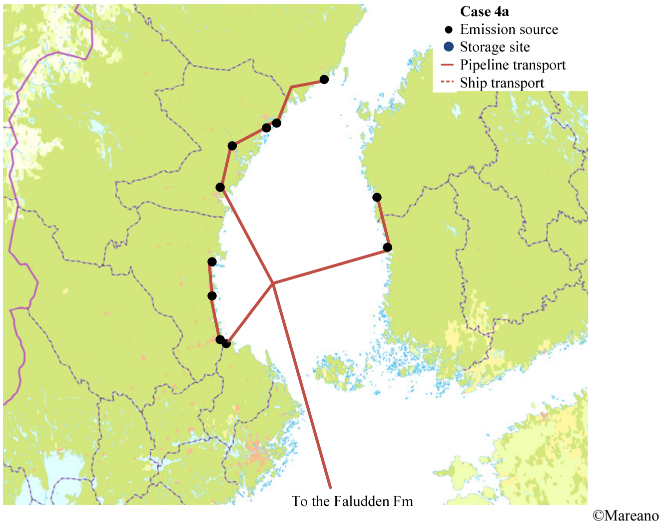


Fig. 5. Assessed transportation, Case 4.

The $CO_2$ is transported in onshore pipeline from each emission source to three intermediate storage hubs. From the hubs the $CO_2$ is transported via three offshore pipelines into one joint pipeline going to the Faludden formation. Table 7 and 8 shows the costs for the transportation in Case 4.

Table 7. Capture cost, Case 4.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (EUR/ton $CO_2$) |
|---|---|---|---|---|
| Stora Enso, Sweden | 1 580 | 216 700 | 51 300 | 42.8 |
| SCA Östrand massfabrikk, Sweden | 1 400 | 197 500 | 45 600 | 43.2 |
| Kosnäsverken, Sweden | 1 330 | 191 800 | 43 500 | 43.7 |
| Vallisvik Bruk, Sweden | 540 | 108 400 | 19 200 | 50.8 |
| Iggesund Paperboard, Sweden | 830 | 141 100 | 28 300 | 46.9 |
| Mondi Dynäs, Sweden | 578 | 113 100 | 20 500 | 50.3 |
| Domsjö Fabriker, Sweden | 577 | 130 000 | 20 100 | 51.9 |
| M-real, Sweden | 1 690 | 222 700 | 52 500 | 43.1 |
| SCA Packing Obbola, Sweden | 460 | 135 800 | 21 400 | 68.8 |
| PVO-Lämpö Oy, Finland | 917 | 148 300 | 30 400 | 45.3 |
| Fortum P&H Oy, Finland | 2 280 | 267 100 | 70 500 | 39.8 |

Table 8. Transportation cost, Case 4

| Case | Transportation mode | Facility | Capture Potential (kt/yr) | Applied distance (km) | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 4 | Pipeline Faludden | All sources | 10 355 | 1 577 | 2 060 000 | 14 000 | 16.5 |

Large clusters, like Case 3 and 4, offer both opportunities and challenges when it comes to $CO_2$ transportation and storage. Pipeline transportation is more cost efficient for larger gas volumes. However, such amounts could provide a challenge for storage as there might be limitations on storage capacity in the Faludden formation. If the storage capacity is reached, the alternative might be to be storage in the Utsira formation. This will increase the transportation distance, which again could favor ship transport.

### 3.5. Case 5: Copenhagen

This case is defined as a "one source to storage", with a short distance to storage. The emission source in this case is Amagerværket, a combined heat and power plant located in Copenhagen, Denmark. Amagerværket emits close to 1 500 000 t $CO_2$/yr. Pipeline and ship transportation to two identified storage sites, the Gedser formation and the Havnsø formation, has been studied. The alternatives are illustrated in Figure 5.

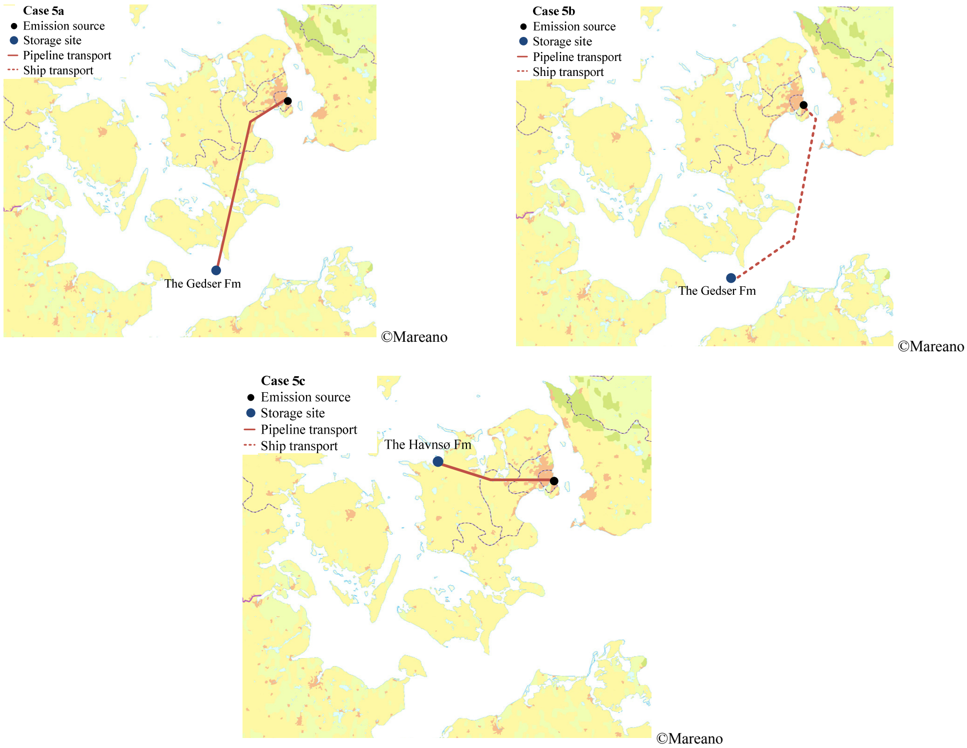


Fig. 6. Transportation alternatives, Case 5

Table 9 and 10 shows the costs for the transportation in Case 5.

Table 9. Capture cost, Case 5.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (EUR/ton $CO_2$) |
|---|---|---|---|---|
| Amagerværket, Copenhagen, Denmark | 1 510 | 207 500 | 48 100 | 40.5 |

Table 10. Transportation cost, Case 5.

| Case | Transportation mode | Facility | Capture Potential (kt/yr) | Applied distance (km) | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 5a | Pipeline Gedser | Amagerværket | 1 510 | 182 | 335000 | 2000 | 18.2 |
| 5b | Ship Gedser | Amagerværket | 1 510 | 176 | 188000 | 13000 | 18.1 |
| 5c | Pipeline onshore Havnsø | Amagerværket | 1 510 | 90 | 175000 | 1000 | 9.2 |

Several transportation options have been evaluated. The lowest transportation cost is found when storing in the Havnsø formation due to the shorter transportation distance compared to transportation to the Gedser formation. There are only small differences in total transportation costs for the two alternatives 5a and 5b, but the variation in capital and operational costs are significant. Public acceptance for onshore storage has been debated in Denmark and it is currently forbidden to store $CO_2$ onshore.

### *3.6. Case 6: Lysekil*

This case consists of $CO_2$ emission sources that are located close to each other on the Swedish west coast. The main source in this cluster is the Preem refinery located in Lysekil. This refinery has an annual capacity of 11.4 Mt crude oil and emits close to 1 700 000 t $CO_2$/yr. The sources in the cluster are located close, and with a moderate $CO_2$ volume of 5 Mt/yr. Storage in the Gassum formation has been considered. A combination of ship and pipeline transportation and exclusively pipeline transportation has been assessed. In alternative 6a all $CO_2$ transportation is made by pipeline, both offshore and onshore. In alternative 6b $CO_2$ from the three largest sources is shipped directly to storage, while $CO_2$ from the remaining sources is transported via onshore pipeline to a hub, and then shipped to storage. The transportation alternatives are illustrated in Fig. 7.

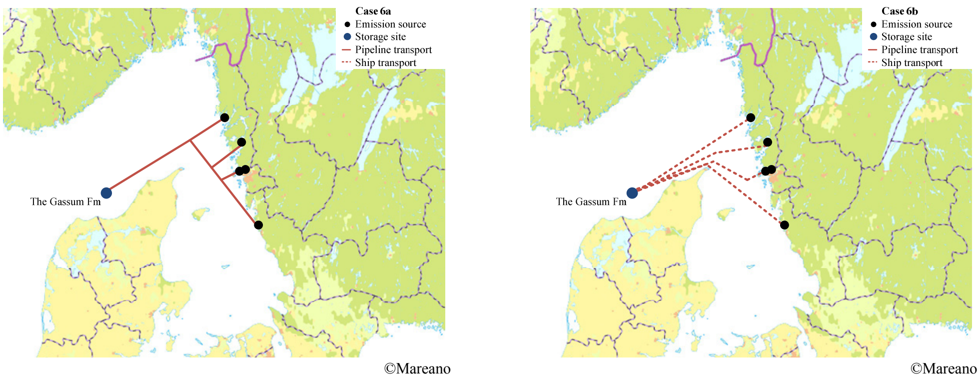


Fig. 7. Transportation alternatives, Case 6.

Capture and transportation costs are given in Table 11 and 12.

Table 11. Capture costs, Case 6.

| Source | Volume $CO_2$ emission (kt/yr) | CAPEX local (kEUR) | OPEX local (kEUR) | Capture cost local (EUR/ton $CO_2$) |
|---|---|---|---|---|
| Preem Petroleum, Lysekil, Sweden | 1 670 | 280 600 | 56 200 | 40.8 |
| Borealis, Stenungsund, Sweden | 690 | 119 500 | 21 900 | 44.9 |
| Preem Petroleum AB, Gøteborg, Sweden | 560 | 110 300 | 19 900 | 45.8 |
| ST1, Gøteborg, Sweden | 350 | 103 600 | 14 000 | 49.2 |
| Rya, Gøteborg, Sweden | 500 | 102 300 | 17 600 | 45.7 |
| Södra Cell, Varø, Sweden | 1 070 | 166 900 | 35 600 | 42.4 |

Table 12. Transportation costs, Case 6.

| Case | Transportation mode | Facility | Capture Potential (kt/yr)* | Applied distance (km) | CAPEX (kEUR) | OPEX (kEUR) | EUR/ ton $CO_2$ |
|---|---|---|---|---|---|---|---|
| 6a | Pipeline Gassum | All sources | 4580 | 539 | 1 233 000 | 5 400 | 21.6 |
| 6b | Ship Gassum | All sources | 4580 | 854 | 501 000 | 5 100 | 19.4 |

## 4. Conclusions

Six case studies have been investigated. $CO_2$ capture costs based on post-combustion MEA technology have been estimated. Alternative $CO_2$ transportation routes and associated costs and permanent storage alternatives have been discussed. Results are preliminary as work in the NORDICCS project is ongoing. The cost of capture is mostly dependent on the captured $CO_2$ volume. With the assumptions made in this study the capture costs are approximately 40-50 EUR/t.

The transportation costs depend on the $CO_2$ volumes and the transportation distance. With the assumptions made in this study the transportation costs are approximately 17-20 EUR/t. Ship transportation is investigated for all cases, where ship and pipeline to the same storage formation is investigated, ship transportation is the least expensive transportation method. Optimizing the transportation with other combinations of ship and pipeline networks could possibly reduce the $CO_2$ transportation costs. The cost of storage is yet to be estimated for any of the cases. However, current indications suggest the storage price to be approximately 7 EUR/t [2].

Even if there are challenges when several sources are to cooperate, there are likely economic benefits from sharing the cost for transport and storage. In addition, $CO_2$ for EOR demands large and stable supply of $CO_2$.

From this study it is can be observed that ship seems more favorable compared to pipeline transportation of $CO_2$ from a cost perspective. Even though the operational cost is higher for ship transportation than for pipeline, the lower investment cost gives a much lower overall cost picture. This is due to the higher flexibility of ships compared to pipeline as it is not likely that pipelines will have any reuse potential. Flexibility in the transportation is likely to be needed as there are large uncertainties when it comes to the timeframe of implementation of CCS in specific plants and uncertainties of storage capacities.

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## References

[1] NORDICCS deliverable report: D4.1.1302 *Nordic $CO_2$ emission maps*
[2] NORDICCS deliverable report: D1.2.1203 *The Nordic CCS roadmap*