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Transport of CO2 in the Nordic region

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Abstract

NORDICCS is a virtual CCS networking platform aiming for increased CCS deployment in the five Nordic countries. This paper reports from work investigating options for CO2 transport infrastructure in the Nordic region. Five specific CCS cases have been selected from which capture is analyzed in detail and from which CO2 transport cost has been calculated assuming CO2 being captured only at the site itself or, assuming the selected capture site develops into a CO2-hub with CO2 from several adjacent sources. In the latter case cost has been calculated defining for what volumes pipeline transport becomes less costly than corresponding ship transport. Additionally, cost for both pipeline and ship transport has been calculated as a function of distance and volume in order to apply these calculations to derive the least costly transport mode for the fifty-five largest sources in the region with a coastal location. Also, the effect on cost for systems that will require ramp-up (i.e. transported volumes increase over time) has been calculated. Finally, an analysis of the potential for build-up of clusters in the region was performed. The work clearly shows that ship transport is the least costly transport option, not only for the five selected cases individually but also for most of the emission sources located along the coastline. The work also shows that ship transport is the least costly transport option for most of the potential clusters in the region during the ramp-up phase. An obvious but still important conclusion is that constrained storage capability and injectivity may have a profound impact on design and cost of a CO2 transport system.

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Keywords: NORDICCS; ship; storage caapacity; injectivity

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1. Introduction

According to [1] the Nordic countries have set ambitious CO_2 emission reduction targets beyond what is actually required by the 2 degrees Celsius target. Combined, the five Nordic countries are targeting a carbon neutral energy system by 2050 reducing domestic emissions by 85% and use international carbon credits to offset the remaining 15%. A large part of the CO_2 emissions in the Nordic countries originate from large energy and emission intensive industries and according to [1], at least 50% of cement plants and 30% of iron and steel and chemical industries need to be equipped with CCS in 2050 to reach the ambitious target in a cost effective way. Furthermore, according to [1], the transport sector will require the most dramatic emission cuts, from 80 Mt CO_2 in 2010 to 10 Mt in 2050. This highlights the potentially important role of Bio-CCS, so-called BECCS, since there are many large-scale biogenic sources in the region from which BECCS may help neutralize emissions from for instance the transport sector.

NORDICCS is a virtual CCS networking platform aiming for increased CCS deployment in the five Nordic countries. There are several reasons why CCS should be considered as an important CO_2 mitigation option in the Nordic region. First and as mentioned above; most emissions are industry related meaning that there are few other options than CCS if emissions are to be reduced substantially, i.e. down to typical requirements to the year 2050 and beyond in line with a 2 degrees Celsius target. Second, most emission sources are located along the coast facilitating build-up of large scale transport and storage systems since ship transport can be utilized initially during the ramp-up phase. Third, sources are located close to each other yielding a good foundation for cluster systems. Fourth, promising potential storage sites have been identified both in the Baltic Sea and in the Skagerrak region, in addition to the many promising sites identified in the North Sea. Fifth and also as mentioned above, there are many large scale biogenic CO_2 emission sources in the region which may help neutralizing emissions in for instance the transport sector providing necessary time for also this sector to become carbon neutral.

This paper reports from work investigating options for CO_2 transport infrastructure in the Nordic region. The paper is organized as follows: Section 2 describes the methodology applied in the work. Section 3 describes the results achieved in the work and Section 4 discusses the results with final conclusions being highlighted in Section 5.

2. Methodology

At the start all emission sources in the region with annual emissions of at least 100 kton, fossil and biogenic, were collected in a database and linked to a Geographical Information System (GIS). In total 286 sources were collected in the database (see Figure 1) with combined emissions in 2010 of 169 Mt of which 108 Mt fossil based and 61 Mt biogenic. The bulk of the biogenic emissions originate in Sweden (30 Mt) and Finland (26 Mt). According to [1], total energy related CO_2 emissions (not including biogenic sources) in the region have fluctuated between 200 and 250 Mt since the 1970s.

Five specific CCS cases have been selected from which capture is analyzed in detail and from which CO_2 transport cost has been calculated assuming CO_2 being captured only at the site itself or, assuming the selected capture site develops into a CO_2-hub with CO_2 from several adjacent sources. In the latter case cost has been calculated defining for what volumes pipeline transport becomes less costly than corresponding ship transport. Additionally, cost for both pipeline and ship transport has been calculated as a function of distance and volume in order to apply these calculations to derive the least costly transport mode for the fifty-five largest sources in the region with a coastal location. Also, the effect on cost for systems that will require ramp-up (i.e. transported volumes increase over time) has been calculated. Finally, an analysis of the potential for build-up of clusters in the region was performed. In all cost calculations, cost data have been derived from [2]. Additionally, basic input parameters to all transport systems were:

- A CO_2 purity of 99% was assumed
- All pipeline segments were designed based on peak flow through that particular segment.
- Cost calculations for pipeline transport started at 70 bar and 20°C at the site of the capture plant and ended at the storage site at a pressure of 70 bar and 0-20°C at sea level. Maximum onshore pipeline pressure was set to 110 bar. Pressure in offshore pipelines was set to 70 bar plus pressure drop depending on distance to the storage site.

- For ship transport it was assumed a max size of 42 ktons, transport at 7 bar and minus 50°C, speed 15 knots, 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 was 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).
- The injection system, i.e. the transport system at the injection site, was based on conservative assumptions on the reservoirs and the individual injection wells injectivity as well as spacing between the injection wells. These are being detailed in Table 1.

Table 1: Applied characteristics of the storage sites used in the transport cost calculations

Reservoir	Total storage capacity, Mt	Reservoir injection capacity, Mtpa	Well Injection capacity, Mtpa	Well spacing, km	Water producers
Faludden, Baltic Sea	300-500	10	1.0[1]	10	Yes
Gassum, Skagerrak	1500-4000	40	1.0	10	Yes
Utsira, North Sea	16000[2]	100	1.0	10	Yes

1: It was recommended to apply a well injection capacity of 0.2 Mtpa in the Faludden aquifer [3].
2: Includes Skade formation.

Figure 1 shows all CO2 sources (green circles) in the Nordic region (apart from Iceland) with emissions of at least 100 ktons in 2010 (fossil based and/or biogenic). Also shown are the five selected cases (red circles) as well as storage sites (light yellow ellipses). Note that shown size and aerial distribution of the storage sites is merely illustrative.

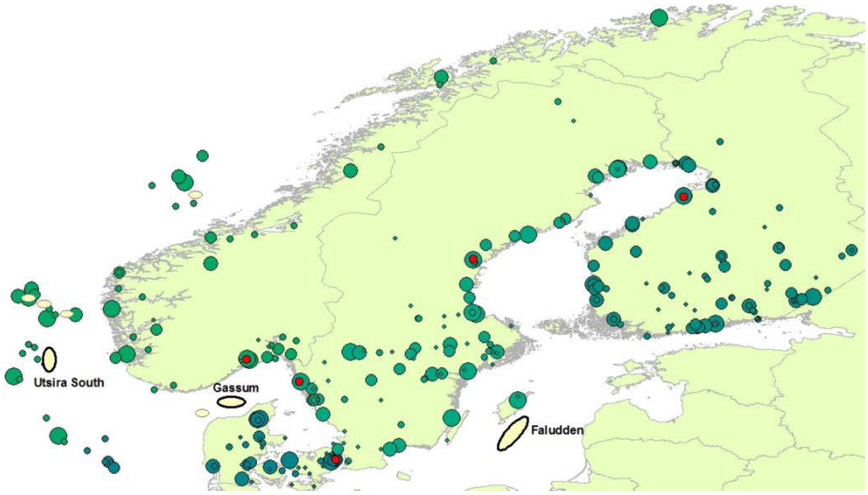

Figure 1: All biogenic and fossil sources in the Nordic region with 2010 CO2 emissions of at least 100 ktons (green circles) with the 5 selected cases shown as red circles. Also shown is the three storage sites applied in this work (yellow ellipses). Note that size and aerial distribution of the storage sites is illustrative only.

3. Results

The first part of the work compared cost for ship and pipeline transport as a function of distance and volume. The main conclusion from this part of the work is that both for the majority of the selected cases as well as for most of the emission sources in the region, ship transport will be the most cost efficient transport mode for each source individually. The results also shows that ship transport is the most appropriate transport mode for most of the potential clusters in the region during a ramp-up phase. The latter is closely related to underutilization of pipelines and risk taking in connection with underutilized pipelines. For distances shorter than 100 km and volumes smaller than 1 Mtpa, e.g. corresponding to a typical collection system in the region containing multiple coastal sources, it has been calculated that onshore pipeline in most cases will be the most cost efficient transport solution. More generally, it can be stated that that the break-even distance where ship transport becomes more cost efficient than pipeline transport increases as the volume increases. Figure 2 shows the result for transport volumes between 5 and 20 Mtpa, i.e. typically a few large single sources combined and clusters of smaller sources. Cost for ship transport is shown as solid lines while pipeline transport carrying the same volume is indicated by dashed lines with corresponding color. The break-even distance where pipeline transport becomes more costly than ship transport is marked by circles, also in corresponding color.

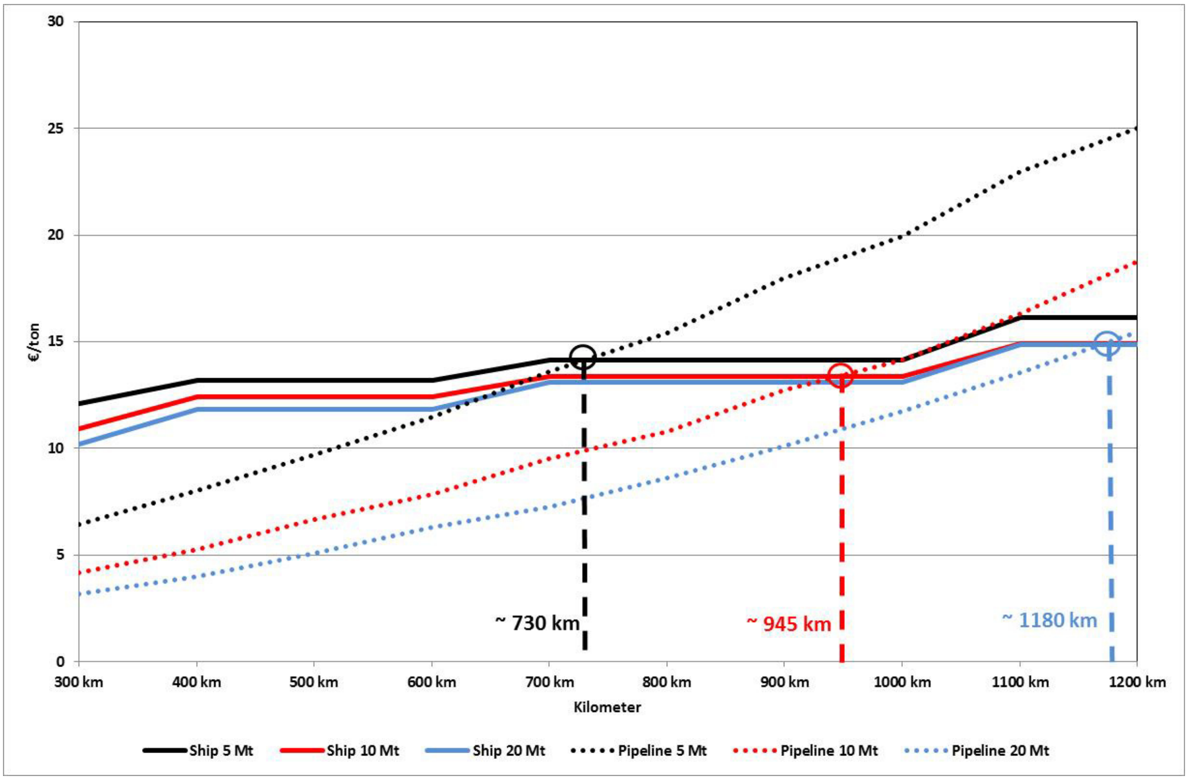

Figure 2: Calculated specific cost for ship (solid lines) and pipeline (dashed lines) as a function of volume and distance. The break-even distance where pipeline transport becomes more costly than ship transport is marked by circles in corresponding color.

For four out of the five selected sources highlighted in Figure 1 (red circles) ship was calculated to be the least costly transport mode, namely the three sources located farthest to the north plus the single source located farthest to the south. Specific cost for these four sources was calculated to range from € 16 to € 22 per ton, primarily due to a combination of relatively low volumes and long transport distances. For the fifth selected case, a refinery on the Swedish west coast, pipeline would be the least costly transport option with specific cost of around € 14/ton. For all the transport schemes, cost is significantly higher than corresponding transport cost calculated for schemes in for instance Continental Europe, see for instance [3].

In order to analyze design and cost of ramping-up large-scale systems three so-called "Grand Schemes" (GS1 to GS3) were designed. The GS includes the sixty-one largest sources in the Nordic region, all located at the coast with combined emissions in 2010 of 82 Mt and an annual capture potential of almost 70 Mt. The GS was calculated in three ways;

- Grand scheme 1 where it was assumed that all sixty-one sources install capture in year one and are included in the same, large pipeline transport system. This "impossible" scheme implies that 61 capture plants can be installed and that at least 140 dedicated CO2-wells can be drilled (assuming that 1 Mtpa can be injected per well and that each injector requires one water producer) within one year. Case 1 is, as indicated, "impossible" in a practical sense and has been included merely to provide a comparison to the two ramp-up cases based on the assumption that this case 1 may represent the most cost efficient system for all the sources involved.
- Grand scheme 2 illustrating ramp-up by pipeline and where it was assumed that one capture plant was been installed each six months in an order arranged according to capture volume, i.e. the higher the capture volume the earlier capture has been installed. This gave a random geographical distribution and the transport system was in this case developed as seven smaller, more regionalized transport systems. All pipeline segments were designed based on the expected plateau flow through that specific segment which means that the investor (the pipeline owner) carries considerable risk.
- Grand scheme 3 illustrating ramp-up by ship and where it was assumed that capture was phased in as in scheme 2 and that all sources have their own individual transport scheme by ship to the storage site.

All transport systems (in all three schemes) were assumed to terminate in a 4-slot subsea template with four well heads and a 50 km umbilical control cable at the storage site, i.e. this has been included in the cost estimates. The cost for additional templates/well heads and CO2 distribution pipelines between templates have not been included. Cost for all transport systems have been calculated up to year 2051. Three storage sites were utilized (see Figure 1); Faludden, Gassum and Utsira. Table 1 shows assumed storage parameters. It is emphasized however that the data listed in Table 1 for the Faludden and Gassum reservoirs are highly uncertain since there is not very much information available on these reservoirs.

Table 1: Applied characteristics of the storage sites used in the Grand Scheme transport cost calculations

Reservoir	Total storage capacity, Mt	Reservoir injection capacity, Mtpa	Well Injection capacity, Mtpa	Well spacing, km	Water producers
Faludden, Baltic Sea	300-500	10	1.0	10	Yes
Gassum, Skagerrak	1,500-4,000	40	1.0	10	Yes
Utsira, North Sea	16,000*	100	1.0	10	Yes

* Includes Skade formation

Grand Scheme 3 which involved separate ship transport for each individual capture plant required 62 ships, one ship to each source apart from Rautaruukki steel plant which required two ships. The largest ship size applied in scheme 3 was 36.4 ktons from Stora Enso's mill in Oulu while the smallest ship size was 5 ktons from Ryaverket combined cycle power plant in Göteborg. Table 2 compares the calculated cost of the three schemes.

Table 2: Investments and specific cost Grand Schemes 1-3

Scheme	Total Transport distance, km	Transported volume 2020-51, Mt	Total Investments million €	OPEX million €	Specific Cost €/ton
Grand Scheme 1	7 738	2 231	19 295	2 752	23.65
Grand Scheme 2	11 746	1 470	15 019	5 002	25.86
Grand Scheme 3	85 333	1 470	8 114	18 251	21.21

Surprisingly, Scheme 1 turns out *not* to be the least costly transport solution. One of the reasons why scheme 1 is so costly is that € 97 million was added for each offshore pipeline segment that was longer than 5 km (there are fifty-three such segments). This cost is based on a series of communications with the industry on the combined cost of landfall, pipeline end module (PLEM) and seabed investigations but it should be stressed that the level of uncertainty is high. Nevertheless, under the assumptions made, ship transport from each single source (Grand Scheme 3) is clearly the most cost efficient transport system. Additionally, shipping carries considerably less risk in a ramp-up case than corresponding pipeline systems since individual pipeline segments in the ramp-up case are designed based on expected plateau flow through each specific segment while new ships just can be added to the system as new capture plants enter the system and the volume increases.

Figure 3 shows the map for the transportation systems designed in Grand Scheme 2 involving seven regional transportation systems (TS 1-6 including TS 2A and 2B, in red font). The numbers in black font shown in Figure 3 illustrates the number of order for installation of the capture plant. The four dashed lines, denoted TS 1, simply refers to the four first capture plants closest to the Faludden reservoir which almost immediately (by 2023) fills up the assumed available injection capacity in Faludden (10 Mtpa, see Table 1) forcing all other sources in the region to Gassum and Utsira. An obvious but still important conclusion that can be drawn from this is that limited storage capacity and injection capacity may have a profound impact on transport cost.

Laying of the pipeline routes for TS 3-5 was done in order to avoid having to climb mountain ranges. However, no considerations were made with respect to terrain, topography and basement rock and their potential effect on cost. For instance discussions with the industry reveal that Nordic conditions often imply that laying of onshore pipelines will have to pass through difficult terrain involving mountains, valleys and solid basement rock which may lead to between 10 to twenty times higher laying cost than corresponding offshore pipelines.

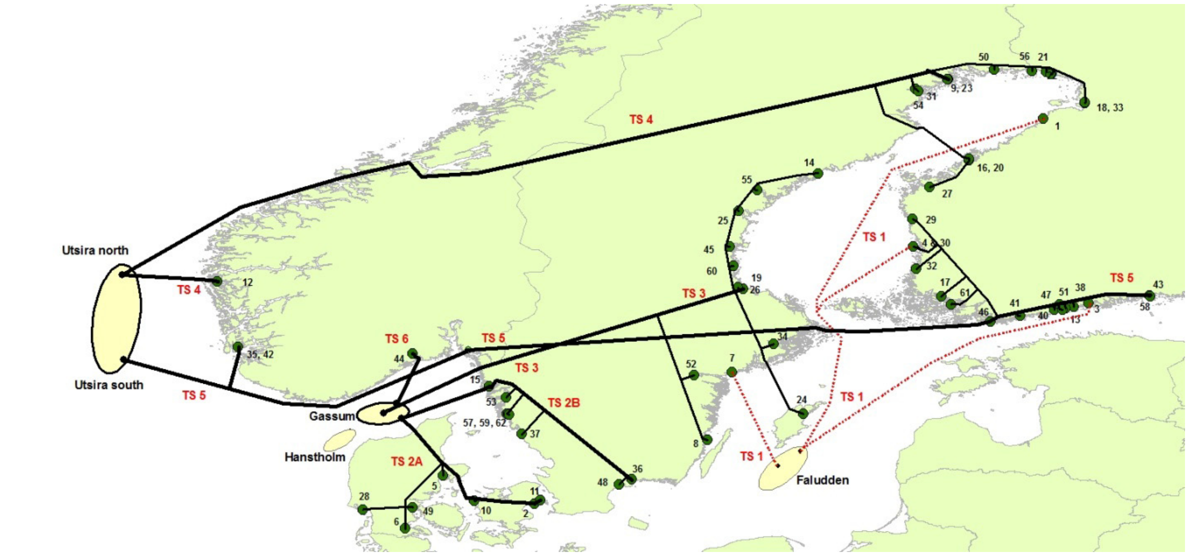

Figure 3: Grand Scheme 2 with seven regional transport systems (TS 1-6 including TS 2A and 2B). TS 1 illustrates four individual ship routes to the Faludden reservoir. The numbers shown at the capture plants illustrate number of order when capture was assumed to be installed. Note that size and shape of storage sites are illustrative only.

In Grand Scheme 2 the CO2-flow is gradually being raised towards plateau flow, i.e. certain pipeline segments are underutilized for several years which of course raises specific cost. Moreover, some individual segments are not added until after 2040 which also raise cost as the system only evaluates cost up to 2051. Table 3 shows when the individual transport systems (TS) in Scheme 2 start, when they reach plateau volume and the specific cost if the system is closed down in 2051 and in 2071.

Table 3: Start-up year, plateau year and specific cost TS1-6 in Grand Scheme 2

Transport system	**Start-up year**	**Plateau reached year**	**CO2 transported Mt (to 2051)**	**Specific Cost 2051 €/ton**	**Specific Cost 2071 €/ton**
TS 1	2020	2023	312.8	11.0	10.8
TS 2A	2020	2043	319.1	13.4	12.2
TS 2B	2027	2049	75.1	34.6	26.1
TS 3	2023	2049	219.7	32.9	27.9
TS 4	2024	2047	338.5	30.5	26.2
TS 5	2026	2050	214.5	56.5	43.9
TS 6	2041	2041	7.1	26.3	26.3
Total system cost	**2020**	**2050**	**1487.0**	**25.9**	**22.8**

The calculations shown in Table 3 indicate a 12% decline in overall specific cost for Grand Scheme 2, from € 25.9/ton to € 22.8/ton if the system is assumed to operate until 2071 instead of 2051.

4. Discussion

The CO2 volumes applied in the calculations above are probably optimistic for two reasons, 1) it is based on 85% capture rate from all sources including from refineries, steel plants and cement plants and 2) sources with biogenic emissions have been included. On the other hand, full scale capture is not likely to be installed on any of the plants included above for at least ten years and probably not for twenty years for most of the plants and by then individual plants may for instance expand or shut down. Thus the point being; the applied CO2 volumes in this report are only indicative. Also, it is becoming increasingly apparent that CCS from biogenic sources will be necessary to meet the 2 degrees Celsius target, see for instance [1, 2].

The calculations of transport cost above clearly indicates that ship transport is the least costly transport mode not only for most of the sources individually but also for most of the potential cluster combinations in the region. In this report it has been assumed that all ship transports terminate at the storage site where it connects to a 4-slot subsea template at the injection site. Cost of the ship *unloading* scheme is based on cost for a so-called sub-merged Turred *Loading* (STL). However, the technology to unload from a ship offshore has not yet been verified and there are also discussions ongoing with regard to positioning of the ship during injection, see for instance [4]. Therefore, it may be more plausible that the ship instead unloads at a hub onshore upon which the CO2 is piped to the reservoir. This has not been investigated in this work.

Obviously, transport system TS 4 in Grand Scheme 2 (see Figure 3) could have utilized storage sites in the Norwegian Sea instead of Utsira in the North Sea like for instance the Garn/Ile aquifers and other aquifers on the Tröndelag platform. This would probably have reduced total investments and specific cost in Scheme 2 but the main objective of the Grand Schemes was to compare cost for large-scale ramp-up by ship and pipeline and to relate this to a system that requires no or little ramp-up. Thus, it was decided to use the same storage sites in all three schemes.

Specific cost for the seven transport systems in Table 3 (and Figure 3) ranges from € 11/ton for TS1 to € 56/ton for TS5 yielding a specific cost of € 25.9/ton for the complete scheme (if the scheme is assumed to operate until 2051). There are several ways to reduce the overall scheme cost like for instance take away parts of a subsystem or entire subsystems, like for instance TS5. Therefore, various ways to reduce overall cost in Grand Scheme 2 will be investigated in future work.

5. Conclusions

The work done in this report clearly shows that ship is the least costly transport option for sources in the Nordic region not only for most of the sources individually but also for most potential cluster combinations during ramp-up. It can also be concluded that cost for CO2 transport in the Nordic region is high compared to cost for similar transport schemes in Continental Europe. This is due to a combination of low volumes and long transport distances.

From the calculations on the various transport systems in Grand Scheme 2 it can be concluded that limited storage capacity and injection capacity may have a profound impact on transport cost.

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