Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 114 (2017) 6860 – 6869

Energy Procedia

13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland

Linking the effect of reservoir injectivity and CO_2 transport logistics in the Nordic Region

Filip Johnsson[1], Ragnhild Skagestad[2], Nils Henrik Eldrup[2], Jan Kjärstad[1]*

[1]*Department of Energy and Environment, Chalmers University of Technology, Gothenburg, SE-412*
[2]*Tel-Tek, 3918 Porsgrunn, Norway*

Abstract

We compare the cost for CO_2-transport by ship with cost for pipeline transport in the Nordic region as a function of transport volume and distance. We also calculate the pipeline volumetric break-even point yielding the minimum CO_2 volume required from a specific site for pipeline to become the less costly transport option and finally, we investigate the effect injectivity may have on the choice of reservoir and transport mode. Most stationary CO_2-emissions in the Nordic region originate from emission intensive industries such as steel, cement and chemical plants and refineries. Typically, their emissions are modest (less than 1 Mt per year) compared to large coal fired power plants, while distances to potential storage sites are considerable, often 300 km or more. Hence, build-up of clusters of emission sources and CO_2-volumes is likely to take time and be costly. At the same time, many of the emission sources, both fossil based and biogenic, are located along the coast line. The results imply that due to modest CO_2-volumes and relatively long transport distances CO_2 transport by ship is the least costly transportation option for most of the sources individually as well as for most of the potential cluster combinations during ramp-up of the CCS transport and storage infrastructure. It is furthermore shown that cost of ship transport increases modestly with increasing transport distance which, in combination with poor injectivity in reservoirs in the Baltic Sea, indicate that it may be less costly to transport the CO_2 captured from Finnish and Swedish sources located along the Baltic Sea a further 800-1300 km to the west by ship for storage in aquifers with higher injectivity in the Skagerrak region or in the North Sea.

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: *Nordic countries; industry; ship transport; ramp-up; injectivity*

* Jan Kjärstad. Tel.: +46-031-772 1454; fax: +46-031-772 3592.
E-mail address: kjan@chalmers.se

Peer-review under responsibility of the organizing committee of GHGT-13.
doi:10.1016/j.egypro.2017.03.1824

1. Introduction

In order to limit the global temperature increase to 2°C the EU has suggested that developed countries should reduce their GHG emissions by 80 to 95% relative to 1990 emissions by 2050 [1]. According to IEA [2] all Nordic countries[†] have long-term climate- and energy-related targets and visions that are ambitious and often surpass EU strategies, but with differences between the countries. Such targets have been even more relevant today, considering the recent agreement in the COP21 meeting in Paris, where it was expressed that global warming should be limited to well below 2ºC [3].

A substantial part of the electricity generated in the Nordic region is generated by hydro, biomass, wind and nuclear energy, thus yielding low overall CO_2-emissions. Also, owners of large coal power plants in Denmark and Finland have announced firm plans to switch to biomass based electricity generation (see for instance [4, 5]). Hence, most of the stationary fossil based emissions in the Nordic region will, in the future, probably arise from the energy intensive industry, such as from the cement and steel sectors and from refineries and chemical plants. Common for these industries, is that CCS has been shown to be a key mitigation measure in a portfolio of measures required to limit the global temperature increase to 2°C [6, 7]. IEA [2] has for instance suggested that 50% of cement plants and at least 30% of iron and steel and chemical industries in the Nordic countries should be equipped with CCS in 2050.

There are almost 300 emission sources in the Nordic region that emit 100 kt of CO_2 or more (biogenic or fossil) and it can only be speculated if and when the various sites will install capture, i.e. CO_2 volume and potential clusters and transportation systems can potentially evolve into any configuration over time. At the same time cost for pipeline transport is sensitive to the volume being transported and most CO_2-sources located in the Nordic region are located along the coast while storage sites are located offshore making also ship transport a potentially feasible transport option. Furthermore, the option of ship transport appears relevant since most emission source in the Nordic countries have relatively low emissions (compared to large coal fired power plants) and long distances to potential storage sites (most sources emit between 100 kt up to 1 Mt CO_2 per year and are located 300 km and more from a potential storage site). Ship transport is also particularly interesting during ramp-up of a CO_2 transport system due to its flexibility allowing addition of multiple capture sites and storage sites over time. Thus, capacity can be added to the system (transport and/or storage) only if and when the need for increased capacity materializes and it is also possible to switch capture and/or storage sites altogether.

At the same time, preliminary analysis of potential storage sites in the Baltic Sea indicate poor storage and injection capacity [8, 9, 10]. This implies that the CO_2 from sources located along the Swedish east coast and the Finnish west coast, may have to be transported between 800 and 1300 km further to the west for storage in reservoirs in the Skagerrak region or in the North Sea. Hence, the potential effect this may have on transport structure and its cost needs to be analyzed in detail.

The main aim of this paper is to conduct a comprehensive assessment of potential CO_2 transport options in the Nordic region taking into consideration both individual emission sites and potential storage reservoirs. The work presented in this paper is based on work done partly in the NORDICCS project [11]. The paper is organized as follows; Section 2 explains the methodology applied in this work while results are given in Section 3. Section 4 discusses the results while main conclusions are given in Section 5.

2. Methodology

In this paper costs of different CO_2 transportation options are analyzed by 1) comparing the cost for ship and pipeline transport as a function of volume and distance and by 2) calculating the pipeline volumetric break-even point, i.e. the volume required from any specific site for pipeline to be the least cost transport alternative in comparison with ship transport. We also analyze the effect injectivity may have on the choice of reservoir and thus also on the transport system.

[†] In this report the Nordic countries refer to Denmark, Finland, Norway and Sweden only.

In Section 3.1 we compare the cost of CO_2 transport by pipeline and ship for increasing volumes and distances. Specific cost for transport by pipeline and by ship are compared for transport distances between 50 and 800 km and for transport volumes between 0.5 and 5.0 Million tonnes per annum (Mtpa).

In Section 3.2 it is assumed that a transport hub may be developed at eight selected sites in the Nordic region. For each of the eight selected transport hubs it is calculated for what volumes (and the corresponding cost) offshore pipeline transport becomes less costly than ship transport to three selected storage sites, i.e. the so-called pipeline volumetric break-even point. Thus, the least costly transport mode from the selected hubs is defined for any combination of clusters transporting CO_2 to the selected storage site. The selected transport hubs represent a relevant geographical distribution of large-scale stationary CO_2 emission sources in the Nordic region. The selected storage sites used for the transport cost calculations represent the reservoir for which we have the best data available in each of the three offshore regions that are relevant for the Nordic region, i.e. Faludden with respect to storage in the Baltic Sea, Gassum with respect to storage in the Skagerrak region and Utsira with respect to storage in the North Sea.

In Section 3.3 it is analyzed how the reservoir injectivity may influence the choice of reservoir. The latter is particularly important in the Nordic region if the assumed storage sites in the Baltic Sea turns out to have modest or poor storage and injection capacity as has been indicated in recent reports [8, 10].

Figure 1 shows all emission sources in the Nordic region with 2010 emissions of at least 100 ktonnes as well as the eight selected sites of large individual CO_2 emission sources where it has been assumed that regional CO_2-hubs may develop (yellow circles with corresponding case number). Also shown is the three selected storage sites (light yellow ellipses). It should be noted that the size and shape of the three storage sites are illustrative only.

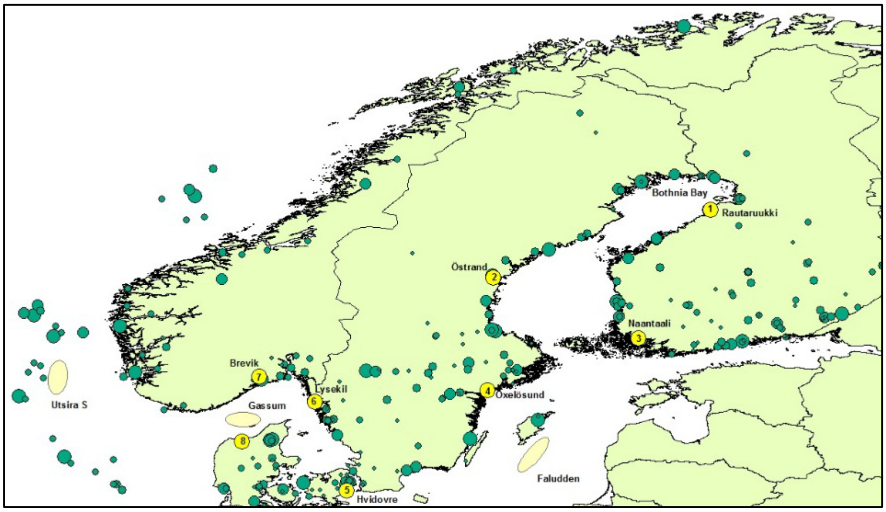

Figure 1: Emission sources in the Nordic region with 2010 emissions of at least 100 ktonnes (green), eight selected sites for development of clusters (yellow circles with case number) plus relevant storage sites (light yellow). From [11].

Basic assumptions and input parameters to *all* transport systems are (*unless otherwise specified*):

a) All cost calculations (pipeline and ship) starts at 70 bar and 20°C at the CO_2-hub and ends at the storage site at a pressure of 70 bar and 0-20°C at sea level. Maximum pressure in offshore pipelines has been set to 70 bar plus pressure drop depending on distance to the storage site. A CO_2 purity of 99% is assumed.
b) Transport distances have been measured in a Geographical Information System to which a "terrain factor" of 10% was added to the offshore distance for both ship and pipeline.
c) Ship sizes are optimized for each transport system but with max size set to 40 000 m^3, transport at 7 bar and minus 50°C, speed 12 knots, 16 hours for loading and 54 hours to unload the CO_2. Cost for

liquefaction, intermediate storage (on barges with volumes corresponding to the size of ships required for the transport), port fees and loading/unloading have been included.

d) Cost has also been included for pumping (from 7 to 70 bars) and heating of the CO_2 from minus 50 up to zero degrees Celsius at the storage site through utilization of waste heat from the ship and use of sea water.

e) All transport systems include cost at the storage site, namely; cost of the required number of subsea templates with well heads, distribution lines between templates and umbilicals.

f) Cost has been calculated using the net present value method, discount rate has been set to 8 % over 25 years (2 years construction, 23 years of operation). All initial cost data have been based on [12, 13] but the initial data has been updated and modified based on industrial experience and discussions with the industry. Cost data has been adjusted to 2014 Years cost level based on Eurostat's Consumer Price Index.

For the plants situated around Bothnia Bay (see Figure 1), the offshore transport distance to relevant storage sites is 1,000 km or more. For pipeline transport this will lead to very large pipelines as the volume increases, in particular if there are no booster stations along the transport route. In this work it was decided to set maximum offshore pipeline diameter to 48 inches. If the diameter exceeded 48 inches two equally large pipeline strings was assumed to be constructed.

3. Results

3.1. Comparing the cost of pipeline and ship transport

Figure 2 compares specific cost for transport by pipeline and by ship for transport distances between 50 and 800 km and for transport volumes between 0.5 and 5.0 Mtpa. Cost for ship transport is shown as solid lines while pipeline transport carrying the same volume is indicated by dashed lines. The break-even points where pipeline transport becomes more costly than ship transport are marked by circles and the corresponding distance is quoted.

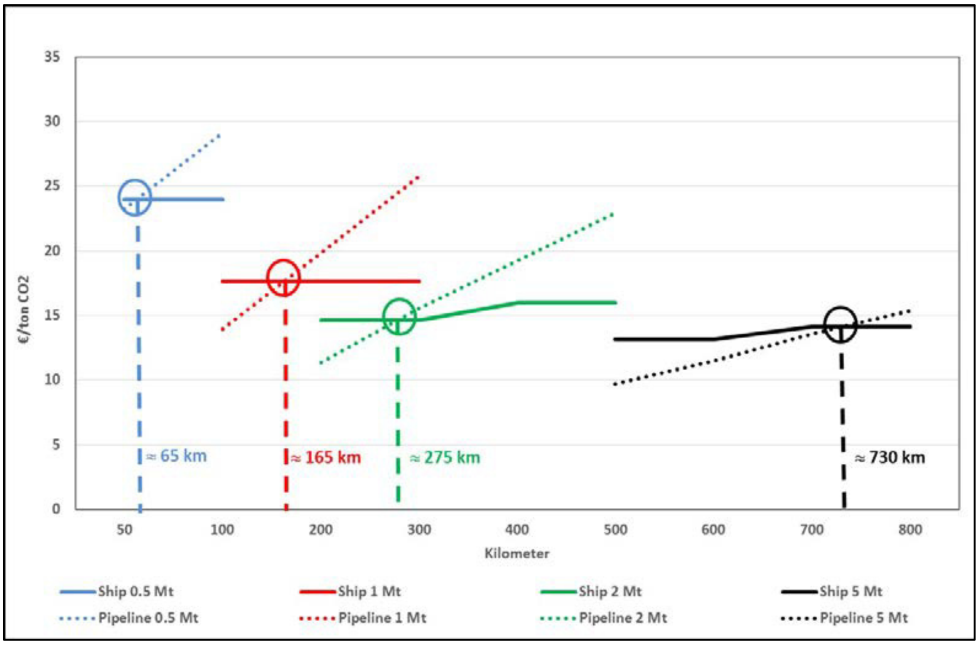

Figure 2: Comparison of pipeline and ship transport cost (in € per ton CO_2) as function of volume and distance.

From Figure 2 it can be seen that the break-even distance where ship transport becomes less costly than pipeline transport increases as the transport volume increases, from roughly 65 km for transport of 0.5 Mtpa to more than 700 km for transport of 5 Mtpa. Figure 2 also implies that;

1) Ship transport cost increases modestly with increasing distance
2) Out of a total of fifty-five sources located along the coast and with an individual annual capture volume of 0.5 Mt or more (assuming 85% capture ratio on 2010 emissions) we can derive that:
    a. Twenty-two of these sources have an individual capture potential between 0.5 and 1.0 Mtpa while at the same time their distance to the nearest storage site exceeds 165 km. Thus Figure 2 indicates that for these sources ship transport will be less costly than pipeline transport.
    b. Another twenty-two of the fifty-five sources have a capture potential between 1 and 2 Mtpa and an individual transport distance to the nearest storage site exceeding 275 km. Thus Figure 2 indicates that also for these sources ship transport will be less costly than pipeline transport.
    c. The Rautaruukki steel plant in Bothnia Bay, Finland (case No 1 in Figure 1) emitted nearly 4.0 Mt in 2010 and has more than 1,000 km transport distance to the Faludden reservoir. Thus, from Figure 2 it can be concluded that also for this plant ship transport will be the least costly transport solution, since this plant has a transport distance exceeding 730 km.

Hence, for at least forty-five of the fifty-five sources with an annual capture potential of 0.5 Mt or more, ship transport will be the least costly transport option for each source individually. Consequently, for the remaining 10 sources, pipeline will be the least costly individual transport option, in most cases due to the short transport distance to the storage site.

3.2. Pipeline volumetric break-even point

Table 1 shows estimated CO_2 captured based on plant 2010 CO_2 emissions and after having applied a capture ratio of 85%, the calculated pipeline volumetric break-even point and the corresponding specific cost for pipeline transport from the eight hubs specified in Section 2 to the three selected storage sites (see Figure 1). For three of the hubs (Brevik, Lysekil and Hvidovre), the pipeline volumetric break-even point and corresponding cost is shown for transport both to the Gassum formation and to the southern parts of Utsira.

Table 1: Pipeline volumetric break-even point and associated cost for selected transport systems

Case		**Storage**	**Distance**	**Site Capture**	**Pipeline Volumetric break-even point**	
no	**Dispatch site**	**site**	**km**	**Potential, Mtpa**	**Volume Mtpa**	**Assc cost, €/tonne**
1	Rautaruukki steel	Faludden	1,070	3.4	NA	NA
2	Östrand Pulp & Paper	Faludden	730	1.2	5.3	14.0
3	Naantali PP/Refinery	Faludden	490	1.7	3.5	13.6
4	Oxelösund SSAB steel	Faludden	280	1.8	3.0	10.0
5a	Hvidovre Coal PP	Gassum	420	2.5	3.0	13.0
5b	Hvidovre Coal PP	Utsira	880	2.5	9.0	13.0
6a	**Lysekil Refinery**	**Gassum**	**165**	**1.5**	**1.2**	**16.0**
6b	Lysekil Refinery	Utsira	615	1.5	5.0	12.0
7a	Brevik Cement	Gassum	180	0.7	1.3	17.0
7b	Brevik Cement	Utsira	560	0.7	4.0	13.0
8	Nordic hub NW Jutl	Utsira	490		3.5	13.6
Site Capture Potential refers to capture from both fossil and biogenic sources at the site						
NA: Pipeline more costly than ship irrespective of volume						

Table 1 indicates that ship transport will be the least costly transport solution for all the selected cases individually apart from case 6a, i.e. from the Lysekil refinery to the Gassum storage site (bold font). It can therefore also be concluded that clusters (multiple capture sites) will be required from any of the selected hubs (apart from case 6a) for pipeline to be the least costly transport mode and, as evidenced in Section 3.1, for most of the sources located along the coast. However, it should be relatively easy to build up the volumes required for pipeline transport to be the least costly transport option from the Naantali site (case 3) and the Oxelösund site (case 4) provided the Faludden aquifer can be utilized for storage. The same applies to the Hvidovre site provided the Gassum formation can be utilized as a storage reservoir.

For Case 1, from Rautaruukki, Bothnia Bay, to Faludden, pipeline transport was calculated to have approximately the same cost as ship for volumes between 12 and 16 Mtpa while for all other volumes ship transport was the least costly transport option. This follows from the fact that for each 17 Mtpa of capacity we will have to add a new pipeline string to the system since we have set maximum pipeline diameter to 48 inches. One possible way to reduce the pipeline cost calculated in this work could be to install land based (or offshore) booster stations along the route. Booster stations (i.e. providing pressure increase) located on land (or on platforms) along the route would lead to that larger volumes could be transported through the pipeline and thus lead to reduced cost for the pipeline itself. Whether this also would lead to lower overall cost for the transport system when including the cost of landfall and booster stations (or platforms and booster stations) is outside the scope of this work.

3.3. Well injectivity and its potential effect on transport cost

In any reservoir there is an optimal CO_2 injection volume, i.e. optimal with respect to full utilization of the storage capacity of the reservoir. Location of individual injection wells and water producers (for pressure management) as well as the CO_2-volume that is injected per well are all important reservoir specific factors that will have an effect on the reservoirs ultimate storage volume. At the same time, drilling of offshore wells is expensive and it is therefore likely that each reservoir will have a specific injection strategy that will be balanced between cost and requirement for storage and injection capacity, see for instance [14, 15].

Drilling of offshore injection wells and water producers represent high costs while at the same time, as indicated in Section 3.1, the cost for ship transport of CO_2 increases relatively slowly with increasing transport distance.

Also, little is known about the storage and injection capacity of the reservoirs in the Baltic Sea. Elforsk [8] states that suitable reservoirs in the southern Swedish sector of the Baltic Sea have relatively poor permeability and porosity characteristics but also that there may be reservoir intervals with better properties where higher injection rates could be safely achieved. According to [8], modelling suggests that 0.5 Mt could be injected per well and year through five injection wells in reservoirs in the Swedish part of the southern Baltic Sea. Mortensen et al. [10] report simulated injection of CO_2 into the Faludden aquifer southeast of Gotland in the Baltic Sea assuming well injectivity between 0.5 and 1.0 Mt per year. The simulations include drilling of 6 injection wells and 5 water production wells [10].

Hence, it seems reasonable to assume an injectivity between 0.5 and 1.0 Mt per well and year in the Faludden aquifer when calculating how different injectivity levels in reservoirs in the Baltic Sea could affect a Nordic CO_2 transport system. In order to analyze the effect injectivity may have on the choice of reservoirs in the Nordic region we calculated the transportation cost for four different assumptions on well injectivity (and consequently also on required number of wells and subsea templates) assuming that all cases transport 4 Mtpa of CO_2 by pipeline or by ship from Naantaali, Finland (see Figure 1 and Table 1). Ship transport cost was calculated as specified in Chapter 2 but additionally, in order to include cost of injection, cost was calculated in two ways; optimizing ship sizes in order to achieve injection rates as close to the maximum as possible (to reduce "off-time" at the injection site as much as possible), i.e. close to 457 tons per hour (4 Mtpa/8,760 hours), or by installation of an "injection barge" with and without an STL (Submerged Turret Loading) at the storage site. The size of the "injection barge" is assumed the same as the size of the transport ship.

Each system includes cost for drilling of injection wells including subsea templates and 4 km pipeline from each well head to the injection point. It is important to emphasize that cost only includes the transport system and drilling of the required number of wells including subsea templates with well heads. Costs for drilling water producers (for pressure management), for umbilicals and for reservoir monitoring have not been included. Table 2 shows the result assuming a total drilling cost of € 50 million per injection well [13, 16].

Table 2: Specific cost (€/tonne) from Naantaali as function of injectivity

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

Cost based on assumed drilling cost of € 50 million per well [13].

As can be seen from Table 2, assuming a well injectivity of 0.5 Mtpa in Faludden indicates that it may be less costly to transport the CO_2 by ship a further 800 km to Gassum and 1,300 km to Utsira provided that at least 1 Mt can be injected per well and year in Gassum/Utsira, in particular if an injection barge is moored at the injection site.

However, assuming that 1 Mt can be injected per well and year in Faludden reduces cost significantly implying that at least 4 Mt needs to be injected per well and year in Gassum for Gassum to be the least costly alternative while even higher injection rates will be required at Utsira. Yet, at these injection levels, the difference in cost between the three storage alternatives is modest, with cost ranging from € 19.2 at Gassum to € 21.1 at Utsira if an injection barge is moored at the site versus € 19.5 at Faludden.

Reducing drilling cost per well by 50% to 25 million Euros changes the results slightly. Assuming a well injectivity of 0.5 Mtpa in Faludden will require the use of an "injection barge" and an injectivity of 1 Mtpa and well in Gassum for Gassum to be less costly while at least 2 Mt will have to be injected annually per well in Utsira in combination with the use of an "injection barge". Assuming instead that 1 Mt can be injected per well and year in Faludden will require use of an injection barge and an injection capacity of 4 Mtpa and well in Gassum for Gassum to be the least costly alternative.

Raising instead drilling cost per well by 50% to 75 million Euros yields that *both* Gassum and Utsira are less costly than Faludden at injectivity levels of 1 Mt per well and year assuming 0.5 Mt can be injected per well and year in Faludden. If Faludden has an injection capacity of 1 Mtpa and well, the results show that Gassum will need an injection capacity of at least 3 Mtpa and well and the use of an "injection barge" in order to be less costly than Faludden.

The calculations above emphasize that cost of drilling the wells may have a large impact on storage and transport systems and even more so if also water producers will have to be drilled. Thus the calculations show that reservoir injectivity may have a profound impact on CO_2 transport systems in the Nordic region.

4. Discussion

Based on industrial experience and discussions with the industry we estimate that the cost calculations presented in this paper have an uncertainty level of +/- 35%. Yet, this level of uncertainty is not likely to alter the main conclusions drawn from this study namely that ship transport is the least costly transport option in the Nordic region and that reservoir injectivity may potentially determine the type of transport system. The former is due to a combination of modest CO_2-volumes and long transport distances for most of the sources in the region while the latter is caused by a combination of poor injectivity in the reservoirs in the Baltic Sea and the clear cost advantage for ship transport over long distances as illustrated in Figure 2.

Another uncertainty is of course the assumed injectivity levels in the Faludden aquifer in Section 3.3 (see Table 2). However, the main objective with the calculations in Section 3.3 is to show the *potential effect* for emission sources located along the Baltic Sea *if* it turns out that the Faludden aquifer and other aquifers in the region have a limited storage and injection capacity. Hence, a primary objective for implementation of CCS in Finland and Sweden should be to investigate further the storage capability of reservoirs in the Baltic Sea.

Transport cost for individual sources presented in this paper are higher than cost levels presented in other reports such as for instance in [17]. There are two main reasons for this, 1) the higher CO_2-volumes and shorter transport distances applied in the ZEP report and 2) basic input assumptions such as 40 years project lifetime in [17] as opposed to 25 years (of which only 23 years operational) applied in this work. The high transport cost calculated in this report will have a large impact on total cost for the whole CCS chain (capture, compression, transport and storage). Yet, as mentioned above, most large scale emission sources in the region are steel, cement, chemical and petrochemical plants and there are for the moment no other technology than CCS that can achieve substantial emission cuts from these industries, which was also recently emphasized by IEA [18].

ZEP [12] and Roussanaly et al., [19] reach conclusions similar to the conclusions reached in this work, namely that pipeline transport cost has significant scale benefits, ship transport cost increases only modestly with increasing distance and the transport distance where ship becomes less costly than corresponding offshore pipeline, increases with increasing transport volume. However, some results differ to the results presented in this work. In particular, [19] conclude that cost for ship transport is competitive at shorter distances than what is obtained in this work, for comparable volumes. Reasons for this are, among other factors, the shorter loading and unloading time applied in [19] and the 10% addition to the overall pipeline length (terrain factor) for pipeline only, whereas in this work a 10% addition has been applied for both pipeline and ship (cf Section 2).

It should be emphasized that some of the technologies required to discharge CO_2 from a ship offshore still need to be demonstrated such as for example the handling of the cold CO_2 prior to injection and positioning of the ship during injection, see for instance [12] and [20]. This could be solved either by heating the CO_2 onboard the ship before injection or the CO_2 could be loaded onto a floating storage barge moored at the injection site where the gas could be stored and heated prior to injection as suggested in Section 3.3 (see Table 2). However, in order to avoid offshore discharge from ship altogether, the ship could simply transport the CO_2 to a land based hub from which a pipeline could transport the CO_2 to the storage site, provided that this still is the least costly overall transport option [11].

Section 3.2 shows that most selected hubs would have to build up cluster systems in order to reach volumes required for pipeline to be the least costly transport alternative. The exception is Case 6a, i.e. the refinery at Lysekil assuming storage in the Gassum formation (see Table 1). An investor may of course still choose pipeline although this is not the economically optimal solution initially, i.e. if the investor is willing to carry the financial risk of underutilization of the pipeline for an unspecified period of time. The key question in this case will be who is willing to carry the financial risk of underutilization. One solution could be that the governments decide that public funding should help to carry the risk either singlehandedly or through some risk sharing. However, the risk of underutilization is one of the reasons why ship transport appears advantageous since this will allow for volumes to build up over time until such volumes have been reached that pipeline is the least costly transport mode (i.e. when the pipeline volumetric break-even point calculated in Section 3.2 and shown in Table 1 has been reached). Also, it should be emphasized that this work is limited to analysis of transportation systems. Yet, for the systems identified in this work to be viable, associated storage sites will need to be certified with accurate estimates of its storage capacity and injectivity including confirmation of its sealing capability. The certification process will obviously also require some level of risk taking (e.g. to determine who will carry the cost of drilling the wells that will be required to assess the storage and injection capacity of the reservoir).

There are regulatory obstacles remaining that may have an impact on the development of CCS and transportation of CO_2 in the Nordic region such as transboundary transport of CO_2, which is prohibited according to the London Protocol. Transboundary transport of CO_2 is however exactly what will be required if the reservoirs in the Baltic Sea turn out to have a poor injectivity and/or storage capacity, i.e. if CCS is to become a viable solution to reduce emissions in Finnish and Swedish industries. Otherwise, the question arises if and how Finnish and Swedish industries can achieve substantial emission cuts without CCS. Another regulatory obstacle is that ship transport is not currently covered by the EUs Emission Trading System meaning that CO_2 transported by ship and then stored still will be considered as emitted CO_2 thereby making ship transport a non-viable solution [21]. The solutions to the regulatory obstacles mentioned above are not straightforward and the risk is that these obstacles may delay CCS with offshore storage (for a thorough review of the various legal obstacles with regard to CCS in the Nordic countries see [21].

5. Conclusions

In this paper we present results from an assessment of CO_2 transportation options in the Nordic countries. Most of the stationary CO_2 emissions in the Nordic region come from emission intensive industries such as steel, cement and chemical industries and refineries characterized by many medium-sized and small emission sources and by large distances between individual sources and to potential storage sites.

Comparing cost for ship and pipeline transport as a function of volume and distance shows that ship transport is the least costly transport option not only for *most of* the sources in the region individually but also for *most of* the potential CCS clusters during ramp-up. This is due to the relatively modest CO_2 volumes in combination with long transport distances and, for the case of clusters, the potential extra cost in connection with underutilized pipelines, in which case the use of ship transport should also reduce the financial risk taking. The results also show that cost for ship transport increases modestly with increasing distance.

The pipeline volumetric break-even point was calculated for eight selected cases (Cases 1-8) located along the coast in Denmark, Finland, Norway and Sweden assuming that local CO_2-hubs could evolve on these sites. Thus, without speculating *how* a local hub can evolve over time with respect to CO_2-volume, i.e. which sources will connect and when in time, these calculations simply render the volumes *required* for pipeline to be the least costly transport mode from that specific site. The results imply that cluster systems involving multiple sources will be required for most of the selected sites for pipeline to become the least costly transport mode. Also, for potential clusters evolving around the four sites situated along the Baltic Sea (Cases 1-4, i.e. Rautaruukki, Östrand, Naantaali and Oxelösund), pipeline transport will only be the least costly alternative if the CO_2 can be stored in the Faludden aquifer for which there is currently only limited information on storage capacity available.

Based on the fact that cost for ship transport increases modestly with increasing distance and that injectivity in the Faludden aquifer may be low ranging from 0.5 to 1.0 Mt per year and well, it is shown in Section 3.3 that it could be less costly to instead transport the CO_2 by ship 800-1,300 km further to the west to storage in Gassum or Utsira. Thus, injectivity may have a profound effect on CO_2 transport and storage systems in the Nordic region.

Acknowledgements

The work has been carried out within the NORDICCS Center of Excellence funded by the Nordic Top-level Research Initiative. Discussions with Per Bergmo, Erik Lindeberg and Dag Wessel-Berg, all at Sintef, Norway, with regard to design of the transport system at the storage site are greatly appreciated. Discussions with John Kristian Økland, Gudmundur Kristjansson, Sven Solvang, Steinar Lervik and Lars Olaf Eide, all at Gassco, Norway, on pipeline and ship transport are also greatly appreciated.

References

[1] EC, 2011. "Energy Roadmap 2050". European Commission. COM (2011) 885/2.
[2] IEA, 2013. International Energy Agency. "Nordic Energy Technology Perspectives 2013".
[3] UNFCC. United Nations Framework Convention on Climate Change. "Paris Agreement".
[4] Dong Energy, 2014. "Dong Energy programme for sustainable biomass sourcing". Version 1.0. December 2014. Available on www.dongenergy.com
[5] Fortum, 2014. "Fortum invests in TSE's new power plant in Naantali, Finland". Press release dated February 10, 2014. Available on www.fortum.com
[6] ZEP, 2013. Zero Emission Platform. "CO_2 capture and storage (CCS) in energy-intensive industries. An indispensable route to an EU low-carbon economy". Available on www.zeroemissionsplatform.eu.
[7] Rootzén J., Johnsson F., 2015. "CO_2 emissions abatement in the Nordic carbon-intensive industry - An end-game in sight"? Energy (2015), Volume 80, pp 715-730.
[8] Elforsk, 2014. "Final report on prospective sites for the geological storage of CO_2 in the southern Baltic Sea". Elforsk report 14:53, March 2014.
[9] Elforsk, 2014. "CCS in the Baltic Sea region – Bastor 2". Final Summary Report. Elforsk report 14:50, September 2014.
[10] Mortensen G.M., Bergmo P.E., Emmel B.U., 2015. "Characterization and estimation of CO_2 storage capacity for the most prospective aquifers in Sweden". Contribution to the 8th Trondheim Conference on CO_2 Capture, Transport and Storage. Elsevier, Energy Procedia. In Press.
[11] Kjärstad J., Skagestad R., Eldrup N.H., Johnsson F., 2016. "Ship transport—A low cost and low risk CO_2 transport option in the Nordic countries". International Journal of Greenhouse Gas Control 54 (2016) 168–184.
[12] ZEP, 2011. Zero Emission Platform. "The costs of CO_2 transport". Available on www.zeroemissionsplatform.eu.
[13] ZEP, 2011. Zero Emission Platform. "The costs of CO_2 storage". Available on www.zeroemissionsplatform.eu
[14] Bergmo P.E., Wessel-Berg D., Grimstad A.-A., 2014. "Modelling of well patterns. Towards maximum utilization of CO_2 storage resources". NORDICCS Technical Report D 6.2.1402.

[15] Wessel-Berg D., Bergmo P., Grimstad A.-A., Stausland J., 2014. ”Large scale CO_2 storage with water production”. Energy Procedia 63 (2014) 3782 – 3794.
[16] Statoil, 2016. “Three wells for the price of one”. Statoil press release May 26, 2016. Available on: www.statoil.com
[17] ZEP, 2011. Zero Emission Platform. “The costs of CO_2 capture, transport and storage”. Available on www.zeroemissionsplatform.eu
[18] IEA, 2016. International Energy Agency. “Nordic Energy Technology Perspectives 2016”.
[19] Roussanaly S., Brunsvold A.L., Hognes E.S., 2014. “Benchmarking of CO_2 transport technologies: Part II – offshore pipeline and shipping to an offshore site”. International Journal of Greenhouse Gas Control 28:283-299 · September 2014. DOI: 10.1016/j.ijggc.2014.06.019.
[20] Skagestad R., Eldrup N.H., Hansen H.R., Belfroid S., Mathisen A., Lach A., Haugen H.A., 2014. “Ship transport of CO_2 – Status and technology gaps”. Tel-Tek report no. [2214090].
[21] Elforsk, 2014. “Legal & Fiscal aspects”. CCS in the Baltic Sea region, Bastor 2 project, Work Package 4. Elforsk report 14:48.