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Ship transport—A low cost and low risk CO_2 transport option in the Nordic countries

Jan Kjärstad[a,*], Ragnhild Skagestad[b], Nils Henrik Eldrup[b], Filip Johnsson[a]

[a] Department of Energy and Environment, Chalmers University of Technology, S412 96 Göteborg, Sweden
[b] Tel-Tek, 3918 Porsgrunn, Norway

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ABSTRACT

This paper investigates CO_2 transport options and associated costs for CO_2-sources in the Nordic region. Cost for ship and pipeline transport is calculated both from specific sites and as a function of volume and distance. We also investigate the pipeline volumetric break-even point which yields the CO_2 volume required from a specific site for pipeline to become a less costly transport option than ship transport. Finally, we analyze possible effects from injectivity on the choice of reservoir and transport mode.

The emission volumes from the Nordic emission sources (mostly industries) are modest, typically between 0.1–1.0 Mt per year, while distances to feasible storage sites are relatively long, 300 km or, in many cases, considerably more. Combined, this implies both that build-up of an inland CO_2 collection system by pipeline will render high cost and that it is likely to take time to establish transportation volumes large enough to make pipeline transport cost efficient (since this will require multiple sources connected to the same system). At the same time, many of the large emission sources, both fossil based and biogenic, are located along the coast line.

It is shown that CO_2 transport by ship is the least costly transportation option not only for most of the sources individually but also for most of the potential cluster combinations during ramp-up of the CCS transport and storage infrastructure. It is also shown that cost of ship transport only increases modestly with increasing transport distance. Analyzing the effect of injectivity it was found that poor injectivity in reservoirs in the Baltic Sea may render it less costly to transport the CO_2 captured from Finnish and Swedish sources located along the Baltic Sea by ship a further 800–1300 km to the west for storage in better suited aquifers in the Skagerrak region or in the North Sea.

Contents

* Corresponding author.
E-mail address: kjan@chalmers.se (J. Kjärstad).

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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 80–95% relative to 1990 emissions by 2050 (EC, 2011). According to IEA (2013) all Nordic countries[1] have long-term climate- and energy-related targets and visions that are ambitious and often surpass EU strategies, but with differences between the countries. Thus, by the year 2050 there is little room for any CO_2 emissions from the Nordic countries.

A substantial part of the electricity generated in the Nordic region is generated by hydro and nuclear energy thus yielding low overall CO_2-emissions and this characteristic appears to become even more pronounced in the future with most of the remaining large coal power plants in Denmark and Finland having announced firm plans to switch to biomass based electricity generation (see for instance Dong Energy, 2014; Fortum, 2014). 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 chemical plants for which CCS has been shown to be a key mitigation measure in a portfolio of measures required to achieve the substantial emission reductions described above (ZEP, 2013; Rootzén and Johnsson, 2015). IEA (2013) suggests that 50% of cement plants, and at least 30% of iron and steel and chemical industries in the Nordic countries will need to be equipped with CCS in 2050.

In 2010, there were 284 sources emitting 100 ktonnes (kt) CO_2 or more (biogenic or fossil) in the Nordic countries with numerous potential combinations into clusters (and volumes). Thus, establishing a transport network over time to connect these emissions sources will allow for different strategies both spatially and with regard to how the transportation network can evolve over time. Moreover, it can only be speculated *if* and *when* the various sites will install capture, i.e. how the CO_2 volume will evolve over time within any given cluster. At the same time it is well known that cost for pipeline transport is highly sensitive to the volume being transported and most large-scale 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. The potential attractiveness of ship transport is further enhanced since each individual emission source in the Nordic countries have relatively low emissions 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). In Europe, industry plants are often considerably larger, more densely located and, in many cases, close to potential storage sites, at least if onshore storage can be considered relevant (Kjärstad et al., 2011). Finally, ship transport is 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. Also, a ship may be sold after use while pipelines instead may incur decommissioning cost. For further discussions on the value of flexibility for ship and pipeline transport see for instance Knoope et al. (2015).

Also, while the western parts of the Nordic region is well endowed with suitable storage capacity the opposite appears to be the case in the eastern part, i.e. in the Baltic Sea region (Elforsk 2014a,b; Mortensen et al., 2015). Since poor storage capacity in the Baltic Sea may add up to 1400 km additional transport distance for sources located along the Swedish east coast and the Finnish west coast, the potential effect this may have on transport structure and its cost needs to be analyzed in detail.

In addition, Finland and Sweden in particular have many large-scale biogenic CO_2 emission sources which, through installation of CCS, could neutralize emissions from other sectors where significant emission reductions may be difficult to achieve in the medium term, such as in the transport sector. Finally, there is also a potential for storage through CO_2 EOR both in Danish and Norwegian oil fields which may become the driving force for start-up of CCS offsetting cost and providing the first necessary infrastructure. Thus, there are several factors that make CCS an interesting mitigation option in the Nordic countries.

Technical feasibility and cost of ship transport of CO_2 has been investigated in several works such as reported in ZEP (2011a), Roussanaly et al. (2014), Skagestad et al. (2014), GCCSI (2011, 2012a, 2013), Ozaki and Ohsumi (2011), Ozaki et al. (2013), Elforsk (2014c). Although these works undoubtedly have improved our understanding of the technological challenges associated with CO_2 ship transport and have provided relevant cost estimates they have not in detail addressed and analyzed the site specific conditions in the Nordic countries related to comparison between ship and pipeline transport. Considering the relatively small emission sources and the coastal location of the Nordic emission sources, it is of particular interest to investigate the cost and conditions for ship transport. Also, while several papers have investigated the role of injectivity on CO_2 storage (Mathias et al., 2009a, 2009b; IEAGHG 2010; ZEP 2011b; Wessel-Berg et al., 2014; Bergmo et al., 2014; Mortensen et al., 2015), site specific analysis of possible effects from injectivity on cost and consequently also on choice of reservoir and transport mode is lacking. The latter is particularly important in the Nordic region where potential storage sites in the Baltic Sea are few and believed to have limited injectivity and storage capacity (Elforsk, 2014a; Mortensen et al., 2015). Thus, 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. Part of the work presented in this paper is based on work done in the Nordiccs project (Kjärstad et al., 2015) but with updated cost data and improved methodology.

This paper is organized as follows; Section 2 explains the methodology applied in this work. Results are given in Section 3 and these are discussed in Section 4 while main conclusions are given in Section 5.

2. Methodology

In this work costs of different CO_2 transportation options are analyzed both by comparing the cost for ship and pipeline transport from specific sites and as a function of volume and distance. This work focuses on offshore pipelines. There are two reasons for focusing on offshore pipelines; 1) there are very few onshore pipelines in

[1] In this paper, the Nordic region refers to Denmark, Finland, Norway and Sweden, i.e. Iceland has not been included.

the Nordic region and it is generally believed that onshore pipelines will have to face considerably local opposition and very long lead times in connection with the approval process and 2) Nordic conditions often imply that onshore pipelines will have to pass through difficult terrain involving mountains, valleys and solid basement rock which may lead to between ten to twenty times higher laying cost (Gassco, 2015) than corresponding offshore pipelines.

We also calculate the pipeline volumetric break-even point to analyze transport options for potential clusters and finally, we evaluate the effect injectivity may have on the choice of reservoir and thus also on the transport system.

In the first part of this work (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 1200 km and for transport volumes between 0.5 and 20.0 Million tonnes per annum (Mtpa).

Secondly, in Section 3.2 it is assumed that a transport hub may be developed at eight *selected* sites in the Nordic region as shown in Fig. 1. 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. In addition to this, in Section 3.3, we also calculate the specific cost for 6 out of the 8 sources mentioned below individually (sources 1 and 2 and 5–8).

The selected transport hubs are chosen so as to represent a relevant geographical distribution of large-scale stationary CO_2 emission sources from north to south in the Baltic Sea, on the Swedish west coast as well as in Denmark and Norway. The selected transport hubs are also the location of the largest CO_2-source in that region and they are each representative with respect to distance to the selected storage sites. The selected transport hubs (with corresponding case numbers) are:

1. Rautaruukki steel plant in Raahe, Finland to storage in the Cambrian sandstone in the Baltic Sea (hereafter denominated Faludden)
2. Östrand pulp mill in Timrå, Sweden to storage in Faludden
3. Naantali coal power plant and refinery, Finland to storage in Faludden
4. SSAB's steel plant in Oxelösund, Sweden to storage in Faludden
5. Avedöre coal power plant in Hvidovre, Denmark to storage in the Gassum formation
6. Preem refinery in Lysekil, Sweden to storage in the Gassum formation in Skagerrak
7. Norcem cement plant in Brevik, Norway to storage in the Gassum formation in Skagerrak
8. Assumed "Nordic hub" at northwest Jutland, Denmark, comprising multiple sources in the Danish, Norwegian and Swedish part of the Skagerrak region to storage in the southern part of Utsira.

The selected storage sites used for the transport cost calculations are the Faludden aquifer in the Baltic Sea southeast of Gotland in Sweden, the Gassum aquifer in the Danish and Norwegian part of the Skagerrak region and the southern parts of the Utsira formation in the North Sea in Norway. The three storage sites are shown in Fig. 1 as light yellow ellipses. It should be noted that the size and shape of the three storage sites are illustrative only. These three storage sites have been chosen since 1) they are the reservoirs 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 and 2) the transport distances to these three sites correspond to feasible transport distance for most of the sources in the region comprising the Baltic Sea, the Skagerrak region and the North Sea.

Thirdly we have analyzed how the reservoir injectivity may potentially influence the choice of reservoir. The latter is particularly important in the Nordic region if the assumed storage sites in the Baltic Sea turn out to have modest or poor storage and injection capacity as has been indicated in recent reports (Elforsk, 2014a; Mortensen et al., 2015).

Fig. 1 includes all sources that emitted at least 100 kt CO_2 in 2010 (green circles) as well as the eight selected sites for transport hubs with corresponding case number (yellow circles). Thus, the assumption is that future emission sources will be similar to today's sources. This is obviously a simplification but this is done since the future plant structure is not known and since this work focus on transportation infrastructure. The assumption is also motivated by the fact that this work is part of a broader work with the aim to assess the future mitigation options of the industries in the region and that a reasonable assumption is that the aim is to maintain the industrial activities in the Nordic region.

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

a) All calculations starts from a centralized CO_2-hub to which one or more capture sites may be connected (see Fig. 1).
b) Captured CO_2-volume corresponds to 85% of 2010 emissions at each individual plant.
c) Only existing plants are considered (a future system when CCS is available may of course differ from the present system)
d) A CO_2 purity of 99% is assumed.
e) Peak CO_2-volumes for design of pipelines are based on 8000 operating hours for each individual source.
f) 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.
g) Maximum pressure in offshore pipelines has been set to 70 bar plus pressure drop depending on distance to the storage site. Maximum onshore pipeline pressure has been set to 110 bar.
h) 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.
i) Transport distances have been measured in GIS (Geographical Information System) to which a "terrain factor" of 10% was added to the offshore distance for both ship and pipeline. For onshore pipelines a terrain factor of 20% was used. No further considerations have been made with regard to terrain, topography along the selected pipeline route or basement conditions.
j) Ship sizes are optimized for each calculated transport system but with max size set to 40 000 m^3 (we assume a density of 1.15 t/m^3), transport at 7 bar and minus 50 °C, speed 12 knots, 16 h for loading (including port manoeuvring) and 54 h to unload the CO_2 (including connections to unloading buoys). Cost for liquefaction, intermediate storage (on barges with volumes corresponding to the size of ships required for the transport), port fees and loading/unloading[2] have been included.
k) Cost for ship transport includes flashing to take the CO_2 pressure down from 70 bar to 7 bar at the CO_2-hub. Cost has also been included for pumping and heating of the CO_2 up to zero degrees Celsius at the storage site through utilization of waste heat from the ship and use of sea water.

[2] Cost for the ship's unloading equipment is based on cost for a so-called Single-Anchor Loading system (SAL) with an estimated capex of € 27.2 million.

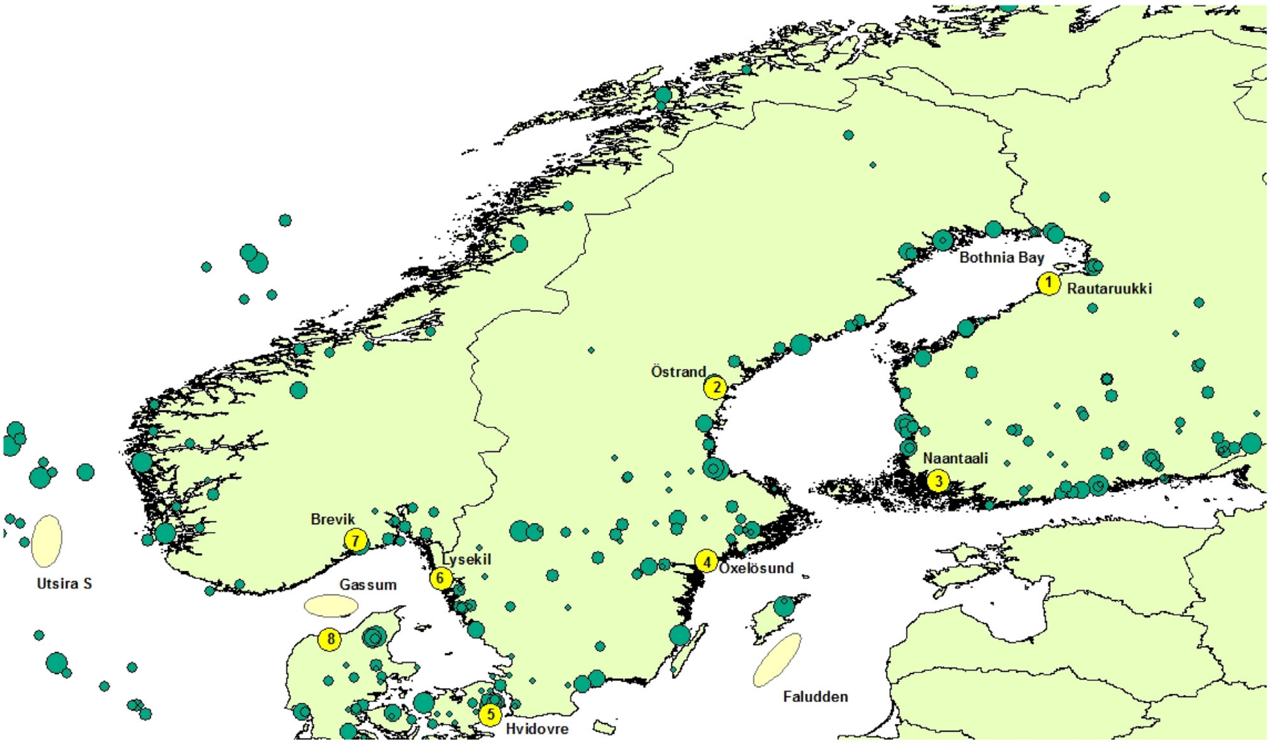

Fig. 1. All emission sources in the Nordic countries (apart from Iceland) with 2010 annual emissions of at least 100 kt (fossil or biogenic, green circles). Also shown are the eight selected transport hubs (yellow circles) used for some of the cost calculations in this work as well as the three applied storage sites (light yellow ellipses). The number within each of the yellow circles refers to the case number of the transport hubs selected in this work (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

l) All transport systems include cost at the storage site, namely; cost of the required number of subsea templates with well heads (depending on total CO_2-volume to be injected and assumed well injectivity), distribution lines between templates and umbilicals. The cost of drilling injection wells and wells for water production (for pressure management) has not been included (apart from in Section 3.4 which includes the cost of drilling injection wells).

m) The injection system, i.e. the transport system at the injection site, has been based on the assumptions that the selected reservoir is able to store the transported volume (i.e. no need for multiple reservoirs for any of the transport systems), that 1 Mt CO_2 can be injected per well per year and that there is a 4 km spacing between each injection

n) 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).[3]

o) All initial cost data have been based on ZEP (2011a,b). However, the data has been continuously updated and modified based on industrial experience and discussions with the industry and has also been adjusted to 2014 Years cost level based on Eurostat's Consumer Price Index (CPI).

For the plants situated around Bothnia Bay (see Fig. 1), the offshore transport distance to relevant storage sites is 1000 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. The largest gas pipeline in the world is the more than 2000 km onshore Yamal pipeline transporting natural gas from Russia to Europe with a nominal diameter (outer diameter) of 56.8 in.[4] while the largest offshore gas pipeline in the world is the 48 in., 1200 km Nordstream pipeline in the Baltic Sea (Gazprom, 2016). Based on discussion with the operator of the Norwegian natural gas transport system, it was decided to set maximum offshore pipeline diameter to 48 in. (Gassco, 2015). Yet, in order to also analyze the effect of setting a maximum pipeline diameter it was decided to not restrict the diameter for the long distance large pipelines dealt with in Section 3.1 while in Section 3.2 the diameter was restricted to maximum 48 in. In the latter case, two pipeline strings were assumed to be constructed if the diameter exceeded 48 in.

Further details with regard to the cost presented in this paper are given in the Appendix A. The cost calculation presented below are estimates and therefore obviously associated with uncertainties. A range in cost levels may arise both due to the choice of technical solutions (selected equipment, size) and due to the existing market situation. The uncertainty levels for the total cost estimates (CAPEX + OPEX) in this report is typically around ±35%.[3]

3. Results

3.1. Comparison between transport cost by pipeline and by ship

Fig. 2 compares specific cost for transport by pipeline and by ship for transport distances between 50 and 1200 km and for transport volumes between 0.5 and 20.0 Mtpa with Fig. 2a giving the results for small single sources (0.5–2.0 Mtpa) and Fig. 2b for large sin-

[3] Cost estimates made in this report should be considered as class 5 estimate according to the rules given by AACE (American Association for the Advancement of Cost Engineering, www.aacei.org).

[4] Even the 4000 km Power of Siberia 1 onshore gas pipeline that is under construction will have a diameter of 56.8 in. (Gazprom, 2016).

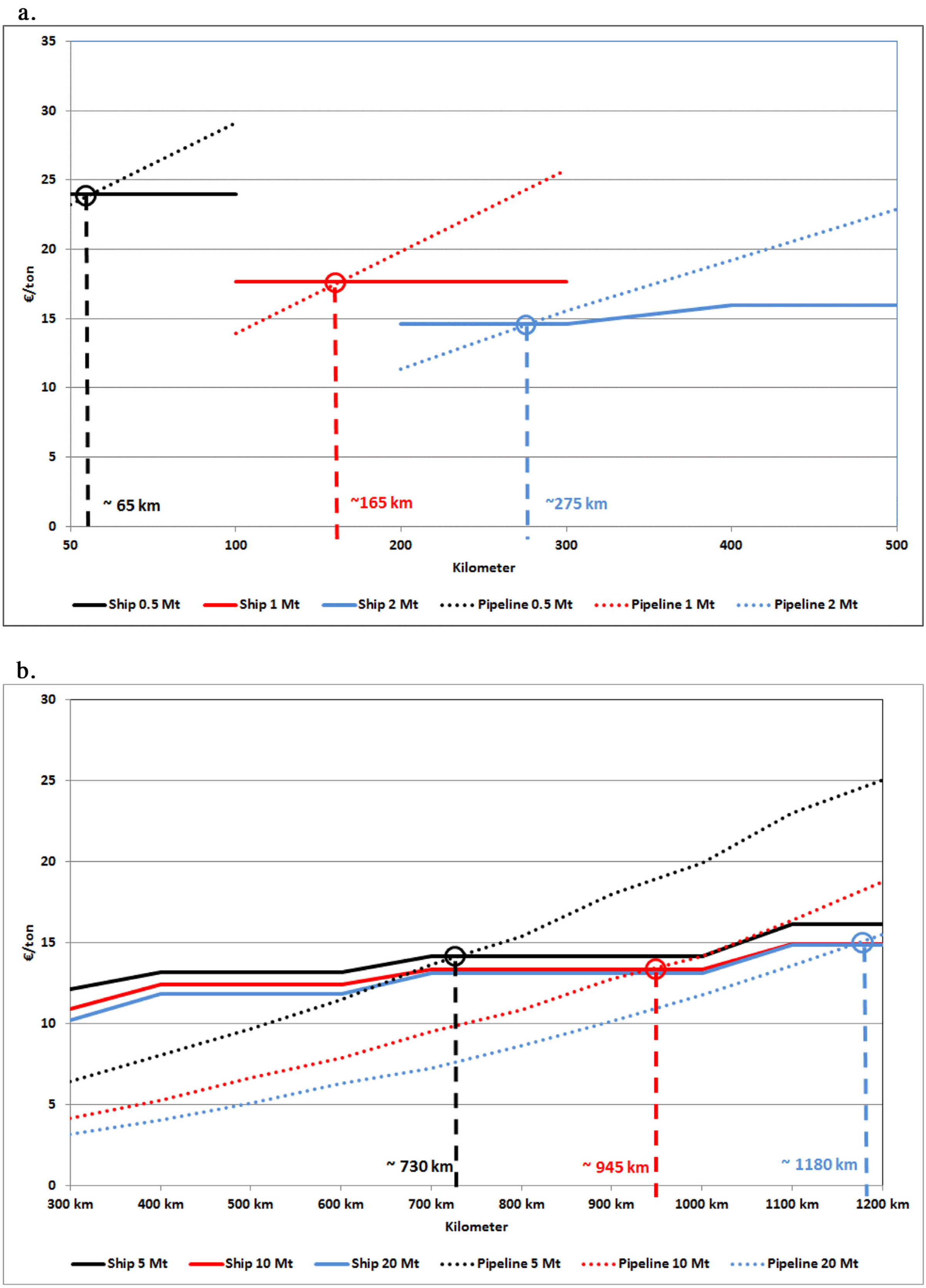

Fig. 2. (a) Comparison of ship and pipeline transport cost, €/t CO_2, as a function of yearly transport volume and distance for transport volumes between 0.5 and 2.0 Mtpa.[5] as a function of yearly transport volume and distance for transport volumes between 5 and 20 Mtpa.

gle sources and clusters (5.0–20.0 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. As mentioned in Section 2 we did not set any restrictions on pipeline diameter in the calculations in this section (the resulting pipeline diameter for the large pipelines in Fig. 2b is given in Table A1 in the Appendix A).

(b) Comparison of ship and pipeline transport cost, €/t CO_2.

As expected, Fig. 2 gives 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 almost 1200 km for transport of 20 Mtpa. From Fig. 2 it can also be seen that the specific cost for ship transport increases modestly as a function of increasing distance, whereas, as expected, pipeline shows a more or less linear cost increase with distance.

There are fifty-five sources with a coastal location and an individual annual capture volume of 0.5 Mt or more (assuming 85% capture) in the region. The combined capture potential of these fifty-five sources amounts to 67 Mtpa. 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. The results given in Fig. 2a indicates that for these sources ship transport will be less costly than pipeline transport. Likewise, another twenty-two of the fifty-five sources mentioned above have a capture potential between 1 and 2 Mtpa and an individual transport distance to the nearest storage site exceeding 275 km, i.e. applying the results in Fig. 2a give that also for these sources ship transport will be the least costly transport mode when considering transportation from each individual source. The Rautaruukki steel plant in Raahe, Finland emitted nearly 4.0 Mt in 2010 and has more than 1000 km transport distance to the Faludden reservoir. Thus, from Fig. 2a,b it can be concluded that also for this plant ship transport will be the least costly transport solution, since this plant has a capture potential in-between 2 and 5 Mt and a transport distance exceeding 730 km. Hence, for at least forty-five out 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, when considering *individual* transportation from each source due to the combination of modest volumes and long distances. Consequently, for the ten remaining sources located along the coast with annual capture volumes of 0.5 Mtpa or more, volumes and distances are such that pipeline will be the least costly individual transport option.

3.2. Pipeline volumetric break-even point for selected cases

Table 1 shows estimated CO_2 captured based on plant 2010 CO_2 emissions (fossil plus biogenic) applying a capture ratio of 85%, the calculated 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 Fig. 1).[6] 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. It should be recalled from Section 2 that we in this section set maximum pipeline diameter to 48 in. based on, among others, discussions with Gassco. This will however, always increase the cost relative to a single line carrying the same volume.

Table 1 indicates that ship transport will be the least costly transport solution for all the cases individually apart from case 6a, i.e. from the Lysekil refinery to the Gassum storage site.

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 (see Table A3 in Appendix A for the detailed cost calculations from Rautaruukki to Faludden). 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 in. It should be noted that in this case, when applying the 48-inches restriction on maximum pipeline diameter, the results deviate from the results obtained for the large pipelines in Section 3.1 (see Fig. 2b).

It should be pointed out however that one possible way to reduce the pipeline cost could be to install land based (or offshore) booster stations along the route and, as can be seen in Fig. 1, there are several sources located further southwards along the Finnish west coast and the Swedish east coast that may be included in a cluster scheme originating from the Rautaruukki plant (or from other plants situated around the Bothnia Bay). 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) has not been assessed in this work and would require more extensive calculations outside the scope of this work.

From Östrand pulp and paper in Timrå (Case 2) it will probably be difficult to reach a capture volume of 5.3 Mt CO_2 per year as indicated in Table 1, all the more so since most of the sources located in the region are small (thus a pipeline connecting to a hub will be costly) and emits biogenic CO_2 for which there are no economic incentives for CCS, at least for the moment. Fig. 3 shows specific cost for Östrand pulp and paper as a function of increasing transport volume.

As can be seen from Fig. 3, pipeline cost (red line) declines rapidly with increasing volume but yet, ship will be less costly for volumes up to around 5.3 Mtpa. Raising the volume further beyond 5.3 Mtpa, to for instance 15 Mt, will reduce pipeline transport cost to € 8 per tonne.

As pointed out above, ship transport will also be the least costly individual transport solution for the Naantaali site on Finland's south coast (Case 3) and from Oxelösund on Sweden's east coast (Case 4). However, both from Naantali and from Oxelösund it should be possible to reach the required volumes for which pipeline transport becomes the least costly transport option (3.5 and 3.0 Mtpa respectively as indicated in Table 1), i.e. if the Faludden aquifer in the Baltic Sea can be utilised as a storage site.

For the three sources located farthest to the west, in Brevik (Case 7), Hvidovre (Case 5) and Lysekil (Case 6), pipeline transport to Gassum becomes less costly than ship already for volumes between 1.2 and 3 Mtpa. This is of course due to the short distances from the anticipated hubs (see Fig. 1) to the selected storage site. Table 1 also indicates, as mentioned above, that pipeline in fact will be the least costly transport solution for the refinery at Lysekil without the need of a local cluster system. Also, since pipeline cost declines rapidly for increasing volumes over short distances, the cost from some of the hubs shown in Fig. 1 may reach very competitive levels, e.g. at a volume of 5 Mtpa, specific cost for pipeline transport from Lysekil to Gassum was calculated to € 4.4/t. Likewise, pipeline transport

[5] In Fig. 2a, cost for ship transport of 0.5 and 1.0 Mtpa appears constant with increasing distance. This is of course not the case but merely a consequence of the calculation method applied in this report where ship transport cost are raised in a step-wise manner not shown for the volumes in question in Fig. 2a. The jump in cost for ship transport occurs when the distance requires that an additional ship will have to be set in to transport the required volume.

[6] Table A2 in the Appendix A yields specific pipeline and ship transport cost for the site specific capture potential given in Table 1 while Table A3 specifies corresponding CAPEX and annual OPEX.

Table 1
Pipeline volumetric break-even point and assc cost for selected transport systems.

Case no	Dispatch site	Storage site	Distance (km)	Site Capture Potential (Mtpa)	Pipeline Volumetric break-even point	
					Volume (Mtpa)	Assc cost, €/tonne
1	Rautaruukki steel	Faludden	1070	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.

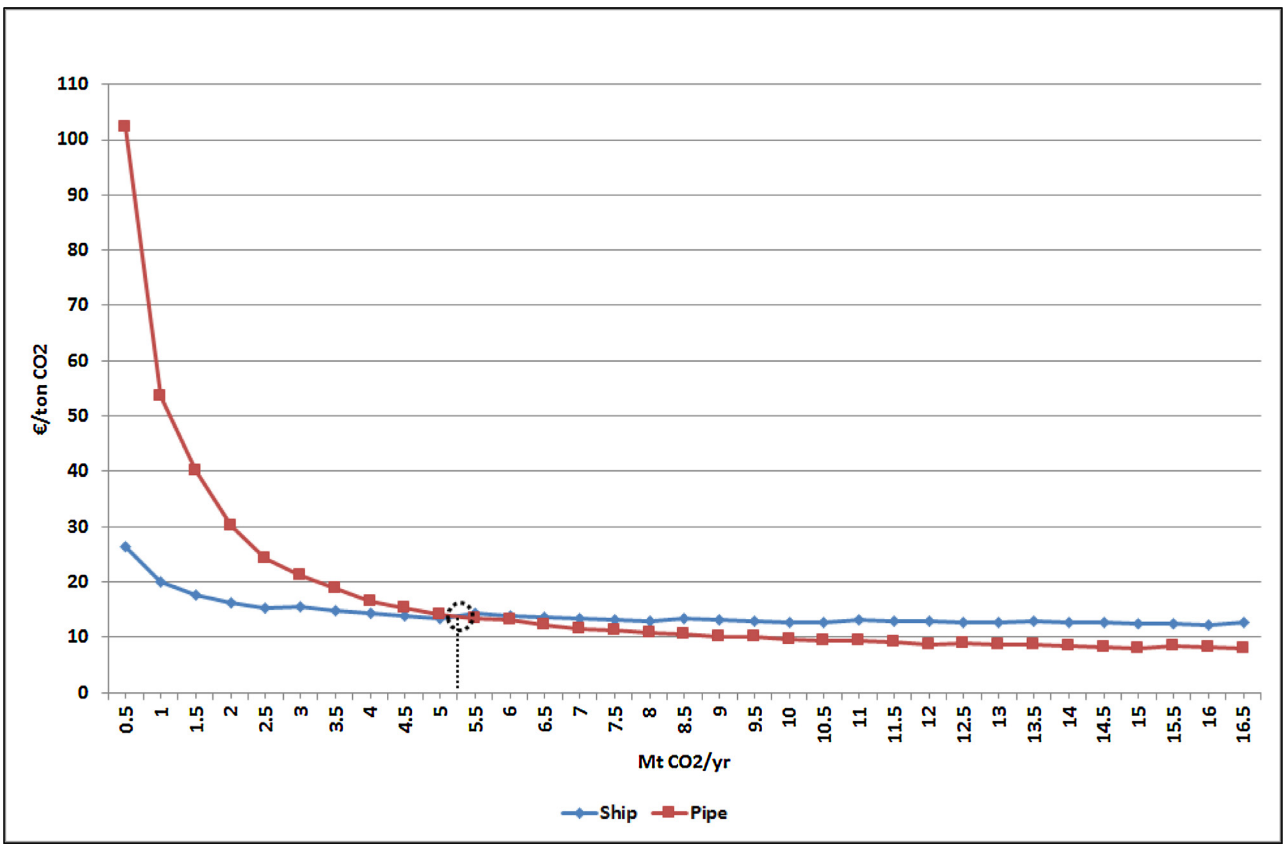

Fig. 3. Specific cost for transport by pipeline (red) or by ship (blue) as function of increasing volume of CO_2 from Östrands pulp mill in Piteå.The cost does not include cost for a collection or distribution system (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

of 9 Mtpa from the "Nordic hub" on Denmark's northwest coast to Utsira was calculated to € 7/t.

As shown in Table 1 all selected cases apart from Case 6a will require build-up of clusters for pipeline to be the least costly transport mode. On the other hand, as has been shown in several reports in literature (see for instance ZEP 2011a; CO2Europipe 2011; GCCSI, 2012b GCCSI, 2012b) and also as illustrated in Fig. 3, pipeline transport has significant benefits of scale. It is therefore obvious that application of CCS on clusters of emission sources should be beneficial for pipeline systems. Yet, it seems unlikely that CCS can be applied to a cluster of CO_2-sources already from the start of operation of a CO2 pipeline, partly because of the large investments that will be required, and partly because installation of a capture plant in many cases will depend on company specific conditions such as for instance the age of the existing plant stock and/or other potential mitigation options than CCS, considered by the owners of the emission sources involved. Thus, a CO_2 transport system consisting of CO_2 from multiple and clustered sources is likely to require several years before it is fully developed. Due to the economy of scale for pipeline transport this raises two questions, 1) how to meet the system requirements during ramp-up in the most cost efficient way and 2) who should take the risk of building pipelines that are likely to be underutilised for a number of years. Fig. 4 shows the effect on specific cost for a pipeline carrying 10 Mtpa over 500 km as a function of the utilization ratio (25, 50, 75% and 100%) reaching 100% utilization after ten (blue line) and five (red line) years, respectively.

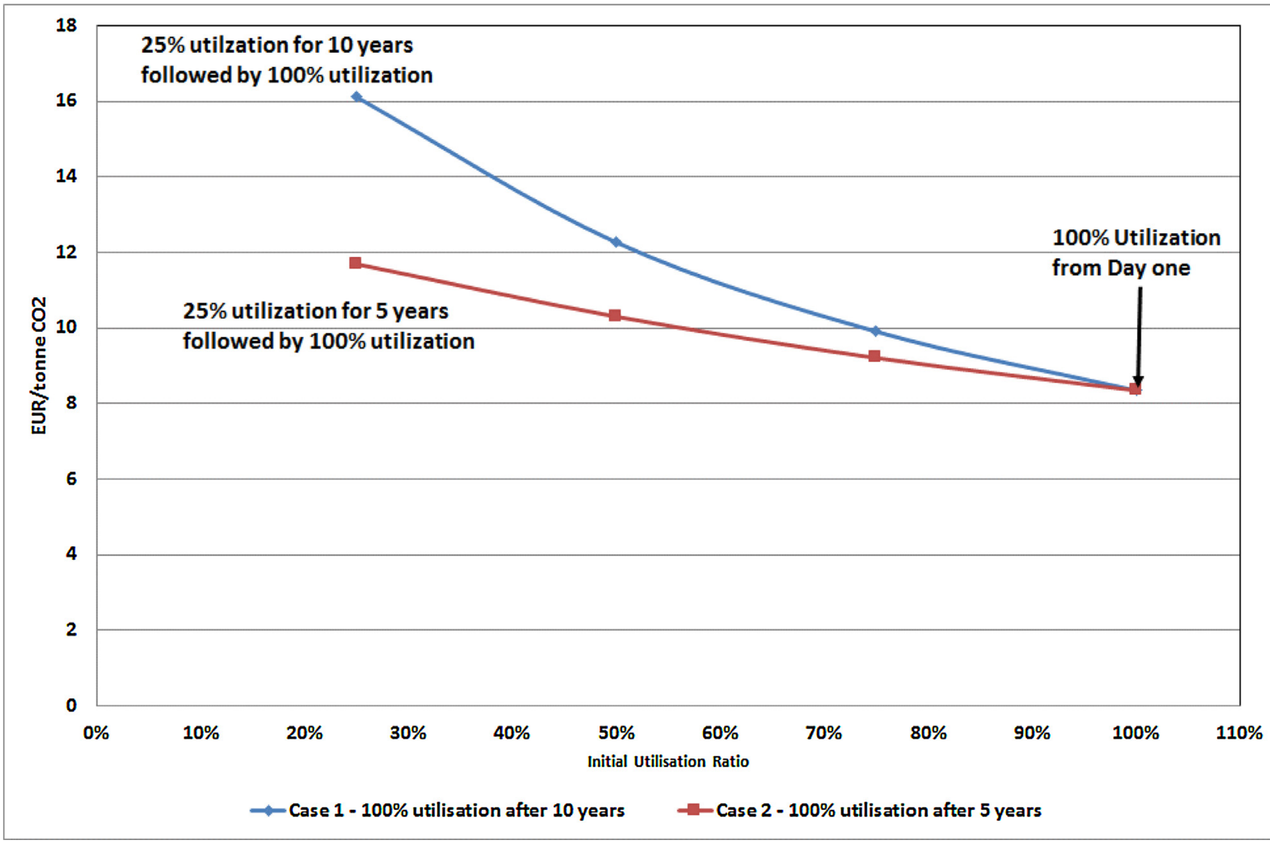

Fig. 4. Specific cost as a function of utilization ratio (25, 50, 75 and 100%) for a 500 km pipeline carrying 10 Mtpa CO_2 and reaching 100% utilization after 10 (blue line) and 5 (red line) years (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

As can be seen from Fig. 4 (blue line), specific cost will almost double, from € 8.4 to € 16.1 per tonne if the pipeline has a 25% utilization ratio for the first ten years of operation as opposed to 100% utilization already from the start. Obviously, the effect on specific cost will be less significant if there is a shorter ramp-up period, e.g. five years as exemplified by the red line yielding around 40% increase in specific cost. In practice, the most cost efficient solution will have to be analyzed for each specific transport case bearing in mind that 1) it is not obvious who will carry the risk for a pipeline risking several years of underutilization and 2) one large single pipeline will probably have less impact on the surrounding environment than several smaller pipelines.

However, as shown in the preceeding chapters, most of the large emission sources in the Nordic countries are located along the coastlines and ship transport is the least costly transport solution for most of the sources if considering individual transportation for each source. Thus, ship transport can be utilised during a ramp-up period until the volumes are sufficient to make pipeline transport the least costly transport mode.

3.3. *Defining the least costly transport solution for selected cases*

All the transport systems described in this section includes the cost described in points l and m, page 6. Thus, cost includes subsea templates with well heads, distribution lines between templates and umbilicals. The cost of drilling injection wells and wells for water production (for pressure management) has not been included.

3.3.1. *Case 1 Rautaruukki, Finland*

Fig. 5 shows three potential transport systems originating from the Rautaruukki steel plant and transporting the CO_2 to three different potential storage sites in the Baltic Sea (Faludden reservoir), Barents Sea (Stö aquifer) and Norwegian Sea (Garn formation), respectively.

For the system to the Faludden site southeast of Gotland in the Baltic Sea we calculated cost for ship transport as a function of increasing volume (recall that it is concluded in Section 3.2 that ship would be the least costly transport option from Rautaruukki irrespective of volume apart for volumes between 12 and 16 Mtpa in which case specific cost would be approximately the same for ship and pipeline transport, see Table A4 in Appendix A). This system *does not include the cost of a collection system.*

The two other transport systems shown in Fig. 5 to the Garn formation in the Norwegian Sea and to the Stö aquifer in the Barents Sea respectively both refer to pipeline transport only and *includes cost for a collection system* from nearby sources taking the CO_2 either to the Rautaruukki plant for further transportation in the bulk pipeline or to a nearby connection point along the bulk pipeline (see Fig. 5). Total length of the transport system from the Rautaruukki plant to Garn and Stö and including the collection systems was estimated to 1770 and 1930 km, respectively.

For the bulk only system to Faludden (no collection system and ship only), specific transport cost range from € 14–22 per tonne for volumes between 20 and 1 Mtpa respectively. Ship transport for the 3.4 Mt CO_2 that could potentially be captured from the Rautaruukki plant alone was calculated to cost around € 16 per tonne. Extending the ship transport system to the Gassum formation and to Utsira raised cost by between 16 and 27% respectively.

Combining the results in Sections 3.1–3.3 for transport systems from the Bothnia Bay to Faludden, it can be concluded that pipeline will be less costly than corresponding ship transport for volumes exceeding around 13 Mtpa, provided that it is feasible to construct offshore pipelines with diameter exceeding 48 in. This follows from

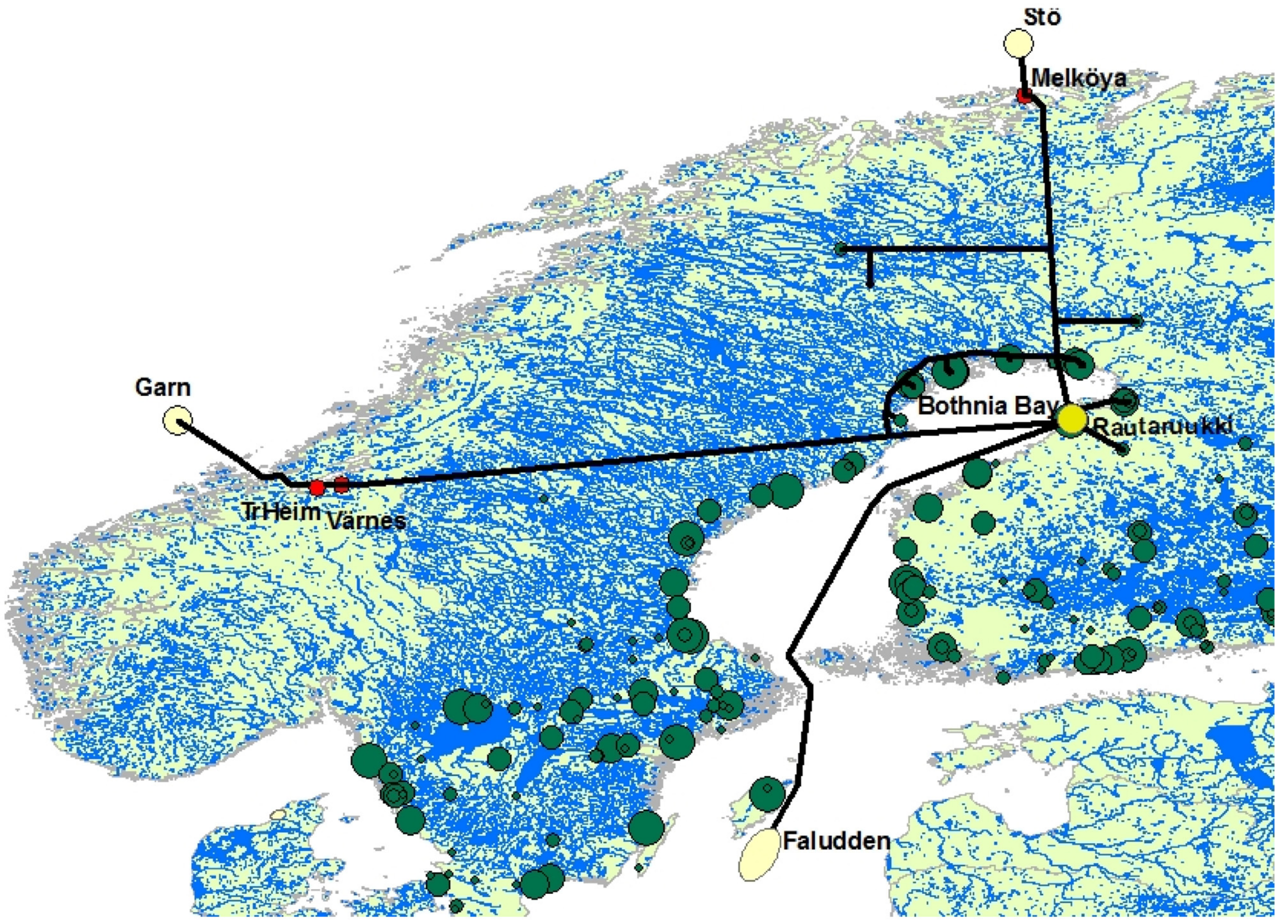

Fig. 5. Bothnia Bay cluster transport system to Faludden in the Baltic Sea, to Stö in the Barents Sea and to the Garn formation in the Norwegian Sea. The yellow circle refers to Rautaruukki steel plant, green circles illustrate the CO_2-sources, red circles illustrate towns or villages along the pipeline route, black lines are pipelines while blue areas illustrate rivers and lakes. A terrain factor of 20% has been applied on onshore pipeline distances while 10% has been applied on offshore distances (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

the simple fact that specific cost for pipeline transport declines as a function of increasing volume (see Table A4). If maximum pipeline diameter is set to 48 in. it is concluded that ship transport will be the least costly transport mode for volumes up to around 12 Mtpa and for volumes exceeding 16 Mtpa. For volumes between 12 and 16 Mtpa specific cost is roughly the same for ship and pipeline transport (see Table A4). However, reaching an annual capture volume of 12 Mt and more will require that most of the sources in the region, including biogenic sources, will have to connect to the transport system. Due to modest CO_2-emissions and long transport distances it will be costly to connect to a centralized pipeline system for some of the sources.

Including the cost of a collection system from 18 selected sources located along the Bothnia Bay, and assuming 100% capacity utilization in all pipelines from day one, it was calculated that onshore pipeline transport to aquifers in the Barents Sea (Stö aquifer) and Norwegian Sea (Garn formation) were the two least costly transport solutions with cost calculated at around € 20/t. Transported volume in these cases ranged between 14.0 and 14.7 Mtpa. It should be stressed however that 1) 100% capacity utilization in all pipelines within the system from day one is highly unrealistic, also considering the fact that several of the plants in the region are small and emits biogenic CO_2 and 2) onshore pipelines may face considerable local opposition and, as evidenced by Fig. 5, the transport routes to Garn and Stö will be complicated with numerous water crossings and, in the case of the pipeline to the Stö formation, the shown pipeline route passes through a Natura 2000 area which may further complicate the approval procedure.

3.3.2. *Case 2 Östrands Pulp mill, Sweden*

Östrands pulp mill emitted 1.4 Mt CO_2 in 2010, almost entirely biogenic. A hub comprising several additional sources may be located at the site of the Östrand plant although it appears more likely that such a hub will be located farther south, typically around Oxelösund with a higher concentration of large and fossil based emission sources (see Fig. 1) and located closer to the Faludden. An injection system in the Faludden reservoir (or other reservoirs) may also be shared with Finnish sources. Assuming 85% capture on the Östrand plant's 2010 emissions yields a CO_2 transport volume of 1.2 Mtpa while the distance to the Faludden reservoir is estimated to 730 km including 10% offshore terrain factor. Ship transport to Faludden is calculated to be the least costly transport option with a specific cost at around € 18/t. This is also further evidenced in Table 1 indicating that at least 5.3 Mtpa will have to be transported from the Östrand site for pipeline to be the least costly transport solution.

3.3.3. *Cases 5–8 sources in the Skagerrak region*

Fig. 6 shows the various transport systems analyzed for the Skagerrak region, i.e. separate pipelines from hubs in each Denmark, Norway and Sweden to Gassum and from the hub located on the northwest coast of Jutland to Utsira. Hubs are shown as yellow circles while other CO_2 emission sources are shown as green

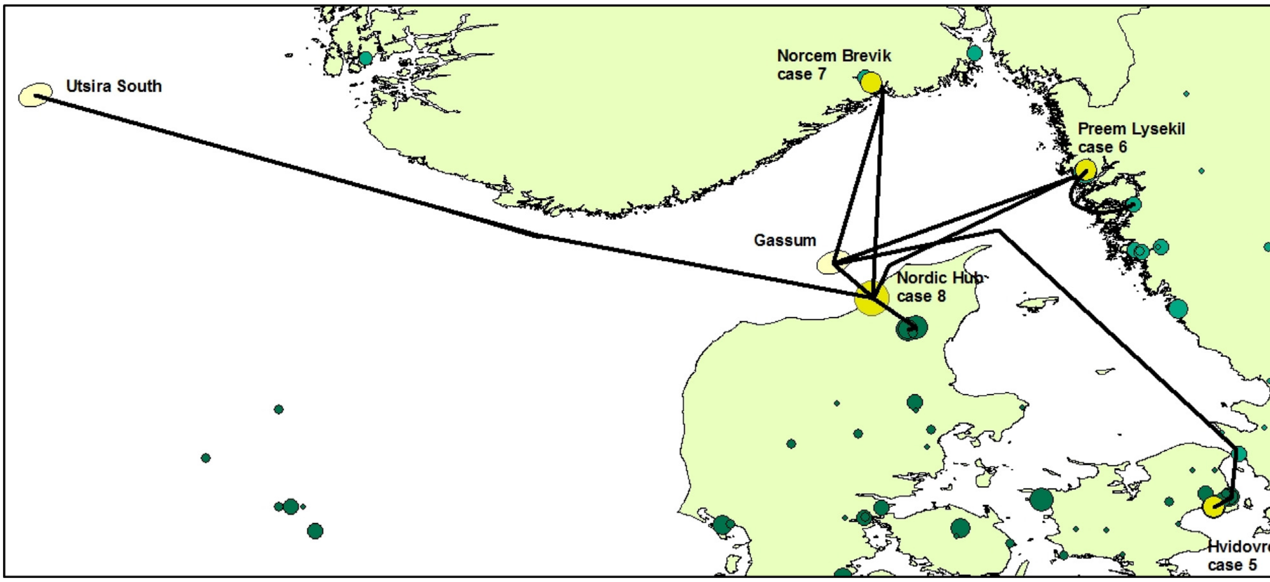

Fig. 6. Calculated transport systems in the Skagerrak region either directly from each country to the Gassum formation or via hub located in northwest Jutland to Utsira.

circles and used storage sites as light yellow ellipses. It should be noted that shape and size of the storage sites are illustrative only.

Cases 5–8 comprise sources in the Danish, Swedish and Norwegian part of the Skagerrak region respectively. Transport cost has been calculated for several CCS systems in the region, both for single sources and for various cluster combinations and both from each separate country as well as for shared systems between countries to two storage sites, namely to the Gassum formation and to Utsira (see Fig. 6). Including the Copenhagen area in Denmark and most of the Swedish west coast raises the potential CO_2 volumes that may be captured in this region significantly. Thus, in this work cost has been calculated as a function of increasing volume from Avedöreverket, Hvidovre, in Denmark (Case 5), from Preem, Lysekil in Sweden (Case 6) and from Norcem, Brevik in Norway (Case 7) assuming that national hubs are being developed at each of these sites. Additionally, cost was also calculated both for ship and pipeline transport from an imaginary "Nordic hub" (shared Nordic collection site) located on the North West coast of Jutland to the Utsira formation (Case 8).

Case 5 referring to Avedöreverket in Hvidovre on Zealand (see Figs. 1 and 6), emitted close to 3 Mt in 2010 of which 45%, or 1.3 Mt, was of biogenic origin. The offshore distance from the Hvidovre plant to the injection site at Gassum is around 420 km. When considering only the Hvidovre plant with a capture potential of 2.5 Mt ship transport is most cost efficient at a cost of around € 13/t. However, already at an annual CO_2 volume of 3 Mt, pipeline becomes the most cost efficient transport solution at a specific cost slightly below € 13/t (see Table 1). Raising the annual CO_2 volume to for instance 8 Mt reduces pipeline transport cost to € 6/t.

Case no 6, Preem's refinery in Lysekil, Sweden, emitted 1.7 Mt CO_2 in 2010. The estimated distance from Preem, Lysekil to the injection site in the Gassum formation is 165 km. Assuming 1.45 Mtpa being captured from Preem, pipeline would be the least costly transport mode at a cost of around € 13 per tonne. In fact, pipeline transport becomes the least costly transport mode for volumes around 1.2 Mtpa and above (see Table 1). Cost is reduced rapidly as the volume is increased and at a CO_2 volume of for instance 5 Mtpa pipeline transport cost is reduced to slightly above € 4/t.

Case no 7, Norcem's cement plant in Brevik, Norway, emitted around 770 kt in 2010. Other large-scale sources in the region include Yara, Noretyl and Esso. Combined capture potential of these four sources is around 2.1 Mtpa. The distance to the injection site at Gassum is 180 km. Ship is the most cost efficient transport mode for the Norcem plant at a cost of around € 22/t (see also Table 1). At volumes around 1.3 Mtpa or more pipeline becomes the least costly transport solution and again, as in the case with Preem's refinery at Lysekil (Case 6), cost declines rapidly as a function of increasing volume, from € 17/t at a transport volume of 1.3 Mt to for instance € 11/t at 2 Mt CO_2 per year.

Case no 8 refers to a central Nordic hub located on Denmark's northwest coast (see Figs. 1 and 6). Cost has been calculated for a transport system from this hub to Gassum and Utsira. The CO_2 was assumed to be collected from sources on the Swedish west coast, Norwegian south coast and from Jutland in Denmark. Total CO_2-volume was 6.8 Mt and the combined transport distance *including the national collection systems* was 560 and 1025 km to Gassum and Utsira, respectively. In both cases, pipeline was calculated to be the least costly transport solution with specific cost ranging from € 16/t for transport to Gassum to €25/t for transport to Utsira.

3.3.4. Summary of least costly transport mode for the selected cases

Table 2 summarises the calculations described in this chapter.

Contrary to Chapters 3.1 and 3.2, Table 2 implies that pipeline is the least costly transport option for most of the cases described in this chapter and also that transport cost can reach relatively low levels well below € 10/t. However, most of the sites shown in Table 2 refer to the southwestern part of the Nordic region (Cases 5–8) with the obvious advantage of having a location relatively close to well defined storage sites. Moreover, all the pipeline systems in Table 2 imply clusters and with volumes exceeding the pipeline volumetric break-even shown in Table 1 apart from the 1.5 Mtpa being transported from Preem's refinery at Lysekil. The results show that pipeline transportation cost in the southwestern part of the Nordic region may decline drastically due to the modest distances if the volumes could be raised, i.e. include more sources, from for instance € 4/t for 5 Mtpa being dispatched from Preem, Lysekil to € 11/t for 2 Mtpa being dispatched from Norcem, Brevik, in both cases to the Gassum formation. Pipeline also appears to be the least cost solution for Case 1, at least if onshore transport across Norway and Sweden can be allowed (see Fig. 5). Yet, as mentioned above, the CO_2-volumes which can add up the required volumes (14–15 Mtpa) include several small sources with emissions down to

Table 2
Transport volume, least costly transport mode, specific cost for transport systems in the Nordic region.

Case No/Dispatch site	Storage site	Distance, km	Least costly transport mode	Cost includes Collection system	Volume, Mtpa	Cost, €/tonne
1 Rautaruukki	Faludden	1070	Ship	No	1–20	22–14
1 Rautaruukki	Garn	1772	Pipeline	Yes	14–15	»20
1 Rautaruukki	Stö	1931	Pipeline	Yes	14–15	»20
2 Östrand	Faludden	730	Ship	No	1.2	18
5a Hvidovre	Gassum	420	Ship	No	2.5	13
5a Hvidovre	Gassum	420	Pipeline	No	4	10
5a Hvidovre	Gassum	420	Pipeline	No	8	6
6a Preem, Lysekil	Gassum	165	Pipeline	No	1.5	13
6a Preem, Lysekil	Gassum	165	Pipeline	No	5	4
7a Norcem, Brevik	Gassum	180	Ship	No	0.7	22
7a Norcem, Brevik	Gassum	180	Pipeline	No	1.3	17
7a Norcem, Brevik	Gassum	180	Pipeline	No	2	11
8a Nordic Hub	Gassum	560	Pipeline	Yes	6.8	16
8b Nordic Hub	Utsira	1 025	Pipeline	Yes	6.8	25

Ëeast costly transport modeërefers to the volumes given in the Table.

100 kt per year, many of which are biogenic and the pipeline routes will be complicated and may meet considerably local opposition, both factors that may increase cost significantly.

3.3.5. Sensitivity analysis

Fig. 7 shows the effect on specific cost for two of the cases described above, Case 2 from Östrand and Case 6 from Preem assuming 50% reduction (blue) and 50% increase (grey) in CAPEX, lifetime, discount rate, fuel cost and electricity cost (see basic assumptions in Section 2).

As can be expected changes in CAPEX has a large effect both on ship and pipeline transport but yet, the relative change is much larger for pipeline transport leading to around 45% change in specific cost both for Lysekil and Östrand. In other words, changing CAPEX by 50% (up and down) leads almost to a corresponding change in specific cost for pipelines. Although the corresponding effect on specific cost also is large for ship transport it is distinctly smaller, around 24% in both cases. Changes in lifetime and discount rate also yield larger effect on cost for pipeline transport than ship, in fact twice as high relative effect on pipeline cost compared to ship cost. Change in lifetime yields a 10% reduction in pipeline specific cost when lifetime is increased by 50% and 33–34% increase in cost when lifetime is reduced by 50%. Corresponding changes for ship transport is 5 and 17%, respectively. The similar relative effect can be observed also for changes in the discount rate but in the opposite direction, i.e. a decrease in discount rate yields a decrease in cost as opposed to lifetime where cost of course increases with a decrease in lifetime. All these differences are obviously due to that pipelines are more capital intensive than the shipping chain.

Changing the cost of electricity has only marginal effect with the largest effect on ship transport, where specific cost increase/decreases by around 0.5% for a 50% increase/decrease in cost of electricity. As expected, changes in fuel cost do have a notable effect on ship transport cost, ranging from plus/minus 9–11% depending on distance, i.e. the shorter the distance, the smaller the effect.

Fig. 7a and b shows that for the Östrand site, ship is the least costly transport mode irrespective of the changes we apply on cost levels. However, for the Lysekil site (Fig. 7c and d), it can be observed that ship becomes the least costly transport option if we *reduce* lifetime or fuel cost by 50% or *increase* the discount rate or CAPEX by 50%.

3.4. The effect of well injectivity on transport cost

In any reservoir there is an optimal CO_2 injection volume, i.e. optimal with respect to full utilization of the reservoirs storage capacity. The optimal injection volume is usually not known and will be specific for each individual reservoir, i.e. each reservoir is likely to have a specific optimal injection strategy with regard to well locations and well injection volume. Also, drilling of so-called water producers (for pressure management) will be essential in order to utilize as much as possible of the reservoirs storage capacity. At the same time, drilling of offshore wells is expensive and hence chosen injection strategy will probably be balanced between cost and requirement for storage and injection capacity, see for instance Bergmo et al. (2013) and Wessel-Berg et al. (2014).

Drilling of offshore injection wells and water producers represent high costs while at the same time, the cost for ship transport of CO_2 increases relatively slowly with increasing transport distance (see Section 3.1). Also, little is known about the storage capability of the reservoirs in the Baltic Sea. According to Elforsk (2014a), modelling suggests that a total of 2.5 Mt CO_2 could be injected annually through five injection wells in reservoirs in the Swedish part of the southern Baltic Sea, i.e. 0.5 Mt could be injected per well and year. Nothing is mentioned in Elforsk (2014a) with regard to drilling of water producers for pressure management. Elforsk (2014a) states that the 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. Mortensen et al. (2015) report simulations of the injection into the Faludden aquifer in the Baltic Sea southeast of Gotland assuming well injectivity between 0.5 and 1.0 Mt per year. The simulations included drilling of 6 injection wells and 5 water production wells (Mortensen et al., 2015). 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 the CO_2 transport system. Thus, it is of interest to investigate for what injectivity levels it would be more cost efficient to instead of injecting the CO_2 into the Faludden reservoir transport the CO_2 by ship another 800–1300 km to the west for storage in the Gassum and Utsira formations. In order to analyze the effect injectivity may have on the choice of reservoirs in the Nordic region we have investigated 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 Fig. 1 and Table 1).

Assuming that annual well injection capacity refers to continuous injection (here assumed 8760 h per year yielding, for 4 Mtpa, 457 tons per hour), this obviously constitutes a problem for ship transport unless there is a permanent “injection barge” moored at the storage site. Ship transport cost has also in this chapter been cal-

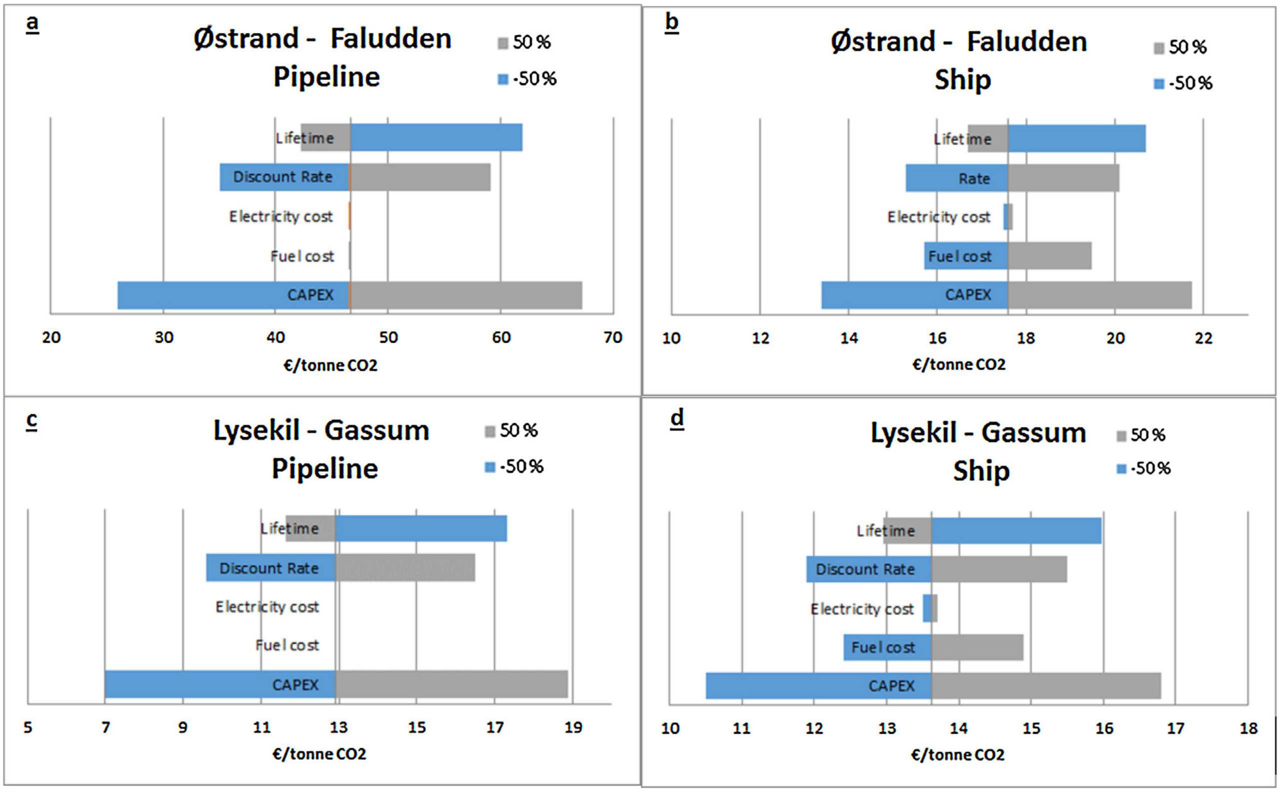

Fig. 7. The specific cost (€/t CO_2) for pipeline and ship transport from Östrand to Faludden (case 2) and from Lysekil to Gassum (Case 6) as obtained from a 50% reduction and increase in lifetime, discount rate, cost of electricity, cost of fuel and CAPEX, relative to basic assumptions as specified in Section 2 (for interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

culated as specified in Chapter 2 but additionally, in order to include cost of injection, ship 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, 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. Costs for drilling water producers may have a solid impact on total cost if the required number of water producers is different in the three reservoirs in any of the four cases described above. Table 3 shows the result assuming a total drilling cost of € 50 million per injection well (ZEP, 2011b; Statoil, 2016).

As can be seen from Table 3, 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 1300 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.

In all, these observations underline the strong influence of the cost of drilling the wells which only will be further emphasized if also water producers will have to be drilled. Obviously, if injection of 0.5 Mt or 1 Mt in Faludden will require drilling of more producers than injection of 1–4 Mt per well and year in Gassum and Utsira, the results above will change towards Gassum and Utsira being even more competitive vis-à-vis Faludden.

4. Discussion

The cost calculations presented above are estimated to have an uncertainty level of ±35%. This is however not likely to change the key conclusions from this study, namely 1) that ship transport will

Table 3
Specific cost (€/t) from Naantaali as function of injectivity.

Assumed well injection capacity	Pipeline	Gassum (ship transport)			Utsira (ship transport)		
		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 (ZEP, 2011b).

be the least costly transport option in the Nordic region, not only for *most of* the sources individually but also for *most of* the potential clusters during a ramp-up period (see Chapters 3.1–3.2) and 2) as shown above low injection capacity in reservoirs in the Baltic Sea may render it less costly to transport the CO_2 to reservoirs in the Skagerrak region or in the North Sea, although this may add between 800 and 1300 km to the total transport distance (see Chapter 3.4). There are several facts pointing in favor of ship transport in the Nordic region such as; relatively low CO_2 volumes (many small sources) also taking into consideration that 85% capture ratio on total emissions for all sources may be optimistic, the long transport distances minimizing risk taking with regard to underutilization of pipeline capacity, most of the sources are located along the coastline and the moderate increase of shipping cost as function of increasing transport distance. Thus, all these factors have implications on CCS systems for countries characterized by small and medium-sized emission sources near coastal regions.

In this work, transport cost for individual sources has been estimated to between € 13 and 22 per tonne (see Table 2). This is significantly higher than the costs presented by ZEP (2011c), of only around 2–5 Euros for a typical power plant (the lower cost refers to coal power plant while the higher cost refers to gas power plant). The reasons for the much lower transport cost achieved by ZEP (2011c) are obvious; the higher CO_2-volumes in combination with the shorter distances but also basic input assumptions such as 40 years project lifetime as opposed to 25 years (of which only 23 years operational) applied in this work. The high transport cost will of course have a profound impact on total CCS cost. ZEP (2011c, 2015) calculated the cost for the whole CCS chain (capture, compression, transport and storage) to range from around € 30–42 per tonne for a typical coal power plant and between € 67–93 per tonne for a typical gas power plant and well below the upper part of this range for most emission intensive industries such as steel, cement and refineries (the latter related to capture from hydrogen production). Yet, it can be commented that there are currently no other technology that can reach deep emission cuts from steel, cement, chemical and petrochemical plants and the importance of CCS in the Nordic countries has also been highlighted by the IEA (2013, 2016).

ZEP (2011a) and Roussanaly et al. (2014) also compare cost of pipeline transport and ship transport. Although there are major differences in assumptions, approach and methodology compared to this work, they both reach conclusions similar to the conclusions reached in this work, namely that pipeline transport cost has significant scale benefits and that ship transport increases only modestly with increasing distance. Both ZEP and Roussanaly et al. also conclude that the transport distance where ship becomes less costly than corresponding offshore pipeline, increases with increasing transport volume. However, the results given by Zep and Roussanaly et al. also differ to this work. In particular, Roussanaly et al. conclude that cost for ship transport is competitive at shorter distances than what is obtained in this work, for comparable volumes. For instance while Roussanaly et al. state that for 4, 8 and 12 Mt annual transport volume, ship transport becomes less costly than corresponding offshore pipeline at transport distances of 325, 375 and 475 km respectively, our work finds that corresponding distances for 5, 10 and 20 Mtpa transport requires around 730, 945 and 1180 km respectively. Reasons for this are, among other factors, the shorter loading and unloading time applied by Roussanaly et al. and the 10% addition to the overall pipeline length (terrain factor) for pipeline only, whereas this work applies 10% addition for both pipeline and ship (cf Section 2). These are both factors that contribute to relatively lower cost for ship transport given by Roussanaly et al. compared to this work.

The transport systems shown in Fig. 5 (Section 3.3) will possibly face additional challenges not fully accounted for in the cost calculations. Onshore pipeline to the Barents Sea and Norwegian Sea will have to pass regions with sensitive nature (e.g. Natura 2000)[7] and involve several crossings of lakes and/or rivers. This has to some extent been accounted for through application of an onshore terrain factor of 20%. However, as mentioned in Section 2, no considerations have been made with regard to the topography or to the basement conditions along the pipeline route. Ship transport far north in the Baltic Sea may encounter severe icing conditions during the winter months potentially making icebreakers necessary. Also this may have been partially accounted for through the application of a 10% offshore terrain factor. Apart from this, it should also be recognized that the onshore pipeline routings shown in Fig. 5 may face more acceptance and permitting problems than offshore pipelines.

With respect to ship transport it should be emphasized that some of the technologies required to discharge 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 ZEP (2011a) and Skagestad et al. (2014). Potential solutions to the former may be that the CO_2 could either be heated 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. 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 of course that this still is the least costly overall transport option (Kjärstad et al., 2015). This specific combination of ship and pipeline transport has not been considered in this work but given that the pipeline transport distance in such a case obviously has to be short and that such a system is likely to involve several sources, i.e. transport relatively high volumes, the added cost can be assumed to be modest.

As mentioned above, the cost calculation presented in this paper are estimates and therefore associated with uncertainties. This is particularly the case with regard to assumed injectivity levels in the Faludden aquifer in Section 3.4 (see Table 3). However, available data on the Faludden aquifer is sparse due to the limited drilling in

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

the region and the main objective with the calculations in Section 3.4 is to show the *potential effect* for emission sources located along the Baltic Sea if it turns out that the Faludden aquifer has a limited storage and injection capacity. It should also be emphasized that large changes in the underlying cost estimates used in this report may change the overall conclusions.

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. Section 3.2 also indicates that underutilisation of a pipeline may have large effect on specific cost (see Fig. 4). The rate of underutilization and the time period passing until full capacity is reached will obviously have the largest impact on the additional cost from underutilization. On the other hand, pipeline transport cost will also decline rapidly as the transport volume increases and one large pipeline will probably have less impact on the surrounding environment than several smaller pipelines. The key question 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, as concluded above, 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).

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. The London Protocol was amended in 2009 to allow for transboundary transport of CO_2 but for the amendment to enter into effect it will require acceptance by two thirds of the Parties to the Protocol, i.e. by at least 30 Parties since there are 45 Parties that have signed the Protocol. As of November 2015 only Norway and UK have signed the amendment to the Protocol while Finland is not even a Party of the Protocol (Elforsk, 2014d). 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 (Elforsk, 2014d). The solution to the regulatory obstacles mentioned above are not straightforward and the risk is that they may delay CCS with offshore storage (for a thorough review of the various legal obstacles with regard to CCS in the Nordic countries see Elforsk, 2014d).

The present work focus on transportation systems. 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 require some level of risk taking (e.g. who will carry the cost of drilling the wells that will be required to assess the storage and injection capacity of the reservoir).

5. Conclusions

An assessment of CO_2 transportation options in the Nordic countries has been performed. 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. In the Nordic countries these industries are characterized by many medium-sized and small emission sources and by large distances between individual sources and to the 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 extra cost in connection with underutilised 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 calculations show that cluster systems involving multiple sources will be required for most of the selected sites for pipeline to become the least costly transport mode. Moreover, for clusters developed 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 provided the CO_2 can be stored in the Faludden aquifer for which there is currently only limited information on storage capacity available.

In Section 3.3 we calculated the transportation cost for each selected case including cost of subsea templates and well heads but excluding the cost of drilling the injection wells (see point l-m, page 6). The calculations yielded ship as the least costly individual transport solution for all cases apart from the refinery at Lysekil (Case 6) with specific cost ranging from around € 14 to € 22 per tonne while pipeline transport cost for Preem, Lysekil is calculated to € 13/t. Raising the volume being transported from each individual case (and thus assuming a cluster) reduces cost rapidly for short distance pipelines originating from Preem, Lysekil and Norcem, Brevik.

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 3.4 that it could be less costly to instead transport the CO_2 by ship 800–1300 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.

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Appendix A.

The basis for the cost calculations are based on industrial experience, discussions with the industry and information given in ZEP (2011a,b) adjusted according to Eurostats CPI .

Table A1
Calculated pipeline diameter Fig. 2b, inches.

	10 Mtpa	15 Mtpa	20 Mtpa
100 km	26	32	38
200 km	28	34	38
300 km	28	34	40
400 km	30	36	40
500 km	30	36	42
600 km	30	38	44
700 km	32	38	44
800 km	32	40	46
900 km	34	42	48
1000 km	36	44	50
1100 km	36	44	52
1200 km	38	48	54
1300 km	40	50	58
1400 km	44	52	60
1500 km	46	56	64

Table A2
Specific pipeline and ship transport cost selected CO_2-hubs.

Case no	Dispatch site	Storage site	Distance (km)	Captured CO_2 (Mtpa)	Pipeline (Cost, €/t)	Ship Cost (€/t)
1	Rautaruukki steel	Faludden	1070	3.4	28.7	16.1
2	Östrand Pulp and Paper	Faludden	730	1.2	48.8	19.3
3	Naantali Power Plant/Refinery	Faludden	490	1.7	30.9	16.1
4	Oxelösund SSAB steel	Faludden	280	1.8	19.8	14.6
5a	Hvidovre Coal Power Plant	Gassum	420	2.5	16.2	14.1
5b	Hvidovre Coal Power Plant	Utsira	880	2.5	30.3	15.8
6a	Lysekil Refinery	Gassum	165	1.5	15.0	15.7
6b	Lysekil Refinery	Utsira	615	1.5	38.5	17.2
7a	Brevik Cement	Gassum	180	0.7	27.3	19.5
7b	Brevik Cement	Utsira	560	0.7	59.3	21.2
8	Nordic hub NW Jutland	Utsira	490	3.5	13.6	13.8

Table A3
Pipeline and ship CAPEX and annual OPEX for selected CO2-hubs, million Euros.

Case No	Dispatch site	Capt Volume (Mtpa)	Distance (km)	Pipeline		Ship	
				CAPEX	OPEX/yr	CAPEX	OPEX/yr
1	Rautaruukki steel	3.4	1 070	1 033	10.3	231	32.0
2	Östrand Pulp and Paper	1.2	730	594	6.4	111	12.0
3	Naantali Power Plant/Refinery	1.7	490	435	4.4	133	15.3
4	Oxelösund SSAB steel	1.8	280	293	2.5	125	15.2
5a	Hvidovre Coal Power plant	2.5	420	419	3.7	166	21.0
5b	Hvidovre Coal Power plant	2.5	880	794	7.7	181	22.8
6a	Lysekil Refinery	1.5	165	209	1.5	110	12.0
6b	Lysekil Refinery	1.5	615	518	5.4	120	13.3
7a	Brevik Cement	0.7	180	209	1.6	79	7.0
7b	Brevik Cement	0.7	560	439	4.9	86	7.7
8	Nordic hub NW Jutland	3.5	490	492	4.9	216	29.6

Table A4
Transport cost (€/t) from Rautaruukki to Faludden as function of volume.

Mt CO_2/year	Ship Rautaruukki-Faludden	Pipeline Rautaruukki-Faludden
1	21.6	77.6
2	17.5	42.2
3	16.6	30.7
4	15.4	25.7
5	15.4	22.1
6	14.6	19.8
7	15.1	18.2
8	14.5	17.1
9	14.1	16.2
10	14.3	15.6
11	13.9	15.2
12	14.1	14.8
13	13.8	14.6
14	14.1	13.6
15	13.8	13.5
16	13.6	13.7
17	13.8	34.1
18	13.6	32.4
19	13.7	32.6
20	13.5	31.2

Maximum pipeline diameter set to 48 in.

Table A5
Assumed time consumption, ship speed and ship size.

Loading (h)	Hours	12
Port Manoeuvring	Hours	4
Connection offshore	Hours	3
Discharge offshore (h)	Hours	48
Disconnection time Offshore)	Hours	3
Total time cons "port handling"	**Hours**	**70**
Ship speed Knots	Nautical mile/hour	12
Maximum ship size	Tonne	40 000
Sailing hours/year	Hours	8400

Table A6
Assumed Fuel consumption tonne/hour, ship size 10,000 m^3.

Loading	0.10
Port manoeuvring	0.13
DP Connection	0.05
DP discharge	0.17
Discharge pumping offshore	0.51
Sea Transit	1.05

Table A7
Applied capital cost for ships (size 10,000 m^3) and equipment.

Cost per ship	kEUR	31 044
DP operation	kEUR	5000
Offshore discharge adaption	kEUR	1875
Predelivery finance cost	kEUR	2844
On-board heating and discharge pumps	KEUR	2081
Engineering and site supervision	kEUR	3104
CAPEX ship	kEUR	***45 949***
offshore terminal (STL)	kEUR	20000
port terminal	kEUR	1000
template + umbilical	kEUR	313
Intermediate storage	kEUR	11875
CAPEX Other	kEUR	***33 188***

DP operation: Dynamic Positioning.
STL: Submerged Turret Loading.

Table A8
Applied O&M, Fuel cost and port fee.

Maintenance (onshore equipment)	4%	of invested capital/year
Maintenance (ship)	2%	of invested capital/year
Electricity	50	EUR/MWh
Cooling water	2.5	EUR/1000 m^3
Fixed O&M ship	750	kEUR/year
Fuel cost	0.7	Euro/tonne
Port fee	2.33	Euro/t CO_2

Table A9
Applied Liquefaction plant Cost – CAPEX/OPEX.

Mt CO_2/year	CAPEX (kEUR)	OPEX (kEUR/Year)
0.5	9073	1109
1.0	14 238	2062
1.5	18 531	2980
2.5	25 828	4764
5.0	40 529	9083
10.0	63 597	17 467
20.0	99 794	33 838
40.0	156 594	65 956

Table A10
Applied pipeline cost (EUR/m).

	100 km	250 km	500 km	750 km	1000 km
48 in.	4559	3 195	2 749	2 613	2 516
40 in.	3666	2 504	2 130	2 015	1 888
36 in.	3299	2 221	1 787	1 714	1 652
30 in.	2455	1 698	1 451	1 382	1 327
28 in.	2316	1 586	1 363	1 266	1 227
24 in.	2100	1 405	1 174	1 108	1 062
18 in.	1879	1 222	1 002	926	888
12 in.	1699	1 085	884	810	775

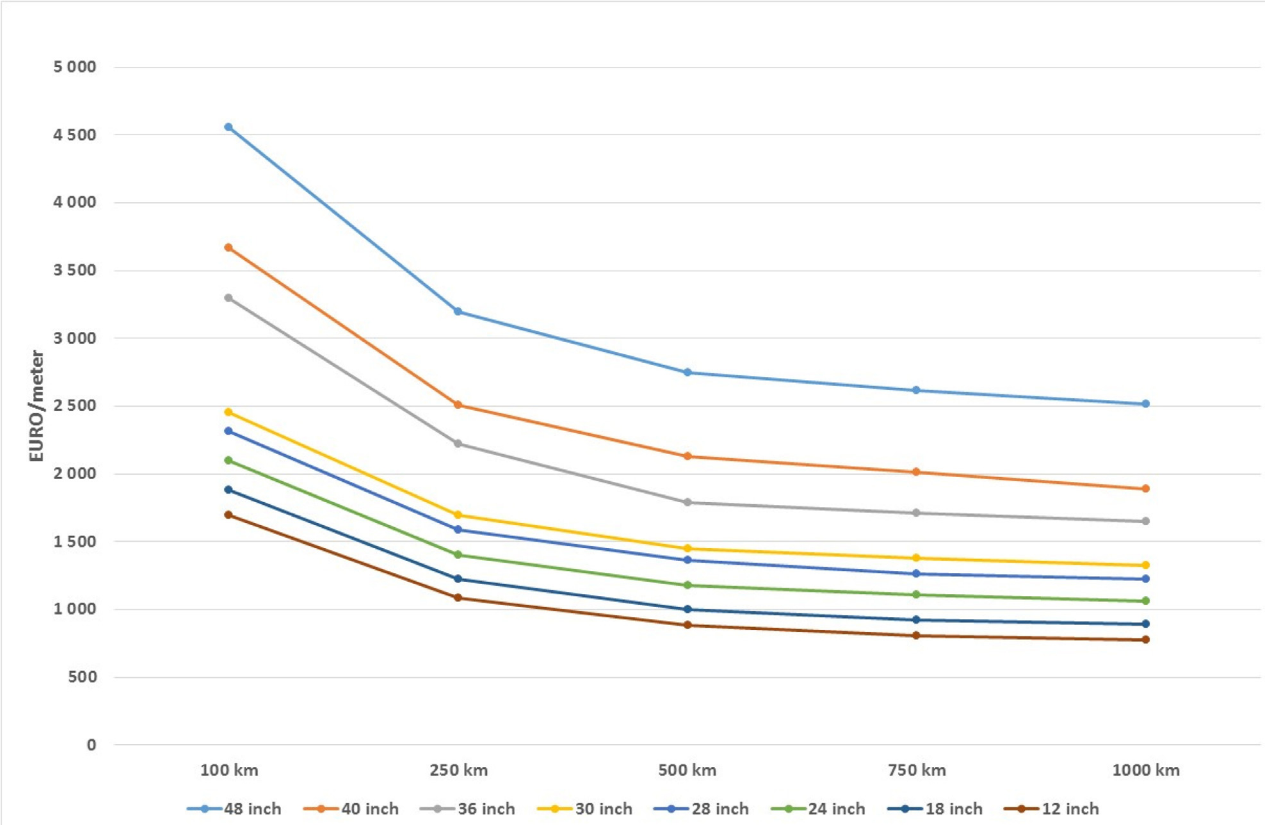

Fig. A1. Applied Pipeline cost in Euros/m and as function of diameter and distance as shown in Table A10.

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