CCS in the Baltic Sea region – Bastor 2

Work Package 5 – Infrastructure for CO_2 transport in the Baltic Sea Region

Elforsk report 14:49

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Preface

Elforsk has organized Bastor2, (Baltic Storage of CO_2), with the overriding objective to assess the opportunities and conditions for Carbon Capture and Storage (CCS) in the Baltic Sea Region. The project is financed by the Swedish Energy Agency, the Global CCS Institute and a number of Swedish industrial and energy companies[1] and runs from June 2012 through September 2014. *panaware ab*, was, together with Chalmers University of Technology commissioned by Elforsk to analyze the potential transport infrastructure for carbon dioxide within the context of Carbon capture and storage (CCS) in the Baltic Sea region.

The authors would like to thank Professor Filip Johnsson at Chalmers and Lauri Kujanpää at VTT Technical Research Centre of Finland for valuable comments, which have considerably helped to improve the report.

[1] The companies are SSAB, Jernkontoret, Svenska Petroleum Exploration, Cementa, Nordkalk, SMA Mineral, Minfo, Vattenfall, Fortum and Preem.

Executive Summary

The Bastor2 project's vision is the development of cross border infrastructure for transport and storage of CO_2 in the Baltic Sea region. Transport is considered the technically most mature part of the CCS supply chain (capture, transport and storage). That is why the main consideration in this work is rather cost than technology. The objective of this report is therefore to present an analysis, including costs, of CO_2 transport solutions and how these could evolve from the first individual CCS projects towards complete transport infrastructure for the CO_2 emitting industries and power plants in the Baltic Sea region.

This work takes its point of departure in selecting the five largest CO_2 sources in Finland and Sweden respectively, as the first projects for CCS implementation. For these ten CO_2 sources, each with annual emissions ranging from 1.1 to 3.4 million tons per annum (Mtpa) the specific cost for the long haul transport (spine) to the two alternative storage locations at Dalders in the Baltic Sea and at Utsira South in the North Sea, were calculated. This analysis was made for both pipeline and ship transport. Additionally, it was assumed that export terminals or "hubs", collecting additional CO_2 volumes from other sources in the region, could be developed at each of the ten selected sites. On this basis, specific cost for the spine was calculated as a function of increasing volume from 1 to 20 Mtpa in steps of 1 Mtpa. The result is a table with not only specific cost of the spine for each selected source itself but also the specific cost of the spine for most relevant combinations of sources (clusters) situated around the ten selected sites. One key feature is the indication of the specific volume required to make pipeline transport more cost efficient than ship transport. These estimates indicate that ship transport is the most cost efficient transport mode not only for each of the ten selected sources individually but also for most of the relevant clusters in the region. The exercise also revealed that the volumes needed to make pipeline transport the less costly solution in most cases would require almost all sources in the area, fossil as well as biogenic, to form a cluster for export through the hub and in three out of four cases, that combined Finnish-Swedish systems would be necessary to reach the required volume. Specific cost for ship transport to Dalders for the ten selected sources ranged from € 12 to € 20 per ton. It should be noted that elements of the ship offshore discharge activity are untested and need technology verification.

Assuming that CO_2-hubs would evolve at the sites of the ten selected sources connecting additional capture plants in the area, cost was calculated for a large amount of feeder (collection) pipelines covering

CO_2-volumes and distances relevant for the region. For instance specific cost for a feeder transporting 0.1 Mtpa CO_2 was calculated to range from € 20.0 to € 60.0 per ton over 100 to 300 km respectively while the corresponding cost for a feeder transporting 1 Mtpa CO_2 over the same distance was calculated to range between € 3.6 and € 9.2 per ton respectively and thus demonstrating the importance of volume to make pipeline transport achieve the lower ranges of specific cost.

At the storage site, the reservoirs' injectivity and storage capacity will decide the selected injection strategy. In order to achieve the highest possible injection rate and to utilise as much of the potential storage capacity as possible, injection will usually be done through several wells distributed in an optimal way thus creating a distribution system at the storage site depending on the actual volume that needs to be stored and on the well injectivity. Assuming a well injectivity of 0.5 and 1.0 Mtpa, specific cost for the distribution system was calculated to € 10 and € 5 per ton respectively.

Out of the five potential cluster systems calculated, the Oxelösund cluster probably offers the best prospects for transport by pipeline. In this region relatively large amounts of CO_2 may be captured and collected which in combination with a relatively short distance to the Dalders injection site indicates that pipeline transport may be less costly than ship transport. Assuming that 13.6 Mtpa CO_2 may potentially be captured in that region, specific cost for pipeline transport to Dalders was calculated to range from € 12.5 to € 15.1 per ton, for the applied injectivity rates of 1.0 and 0.5 Mtpa per well, respectively.

The study concludes that ship transport for most of the selected hubs and clusters is the most attractive transport solution. The main reason is that shipping offers the lower cost and also provides the lower capital risk. This implies a deviation from earlier publications and is attributable to the fact that both the Finnish and Swedish individual sources account for relatively low annual emissions and are geographically more distributed in comparison to the large coal or gas fired power stations in continental Europe and in the UK, often referred to in previous literature.

It is concluded that shipping could simplify CCS deployment, thanks to its inherent nature of comparatively low capital cost and with a near perfect scalability. This is under the assumption that there is a competitive CO_2 shipping market in place. This facilitating role of shipping was found applicable to four critical phases of CCS deployment:

- To facilitate the transport element in the characterization of an offshore geological storage site.
- For the transport leg of CCS demonstration projects, shipping could offer opportunities to share cost. Particularly interesting is

the possibility to share resources, risk and costs for geological storage if transport to the North Sea should be an option, where the geological risk is currently considered much lower than in the Baltic Sea.

- Following successful demonstration projects, wider, large scale deployment could be based on ship transport.
- Should Baltic Sea storage offer less storage capacity than required, CCS deployment could be based on ship transport. This would enable an approach to first use (and possibly deplete) Baltic Sea storage and then turn to storage at an alternative location, likely in the North Sea.

Results from the Zero Emission Platform (ZEP, 2011) and the CO_2 Europipe (2011) projects are used as benchmark for the cost estimations. These comparisons show strong correlation between the presented specific costs for the various transport assignments. It should be noted, however, that the total, specific transport costs in the Baltic Sea region are considerably higher than those presented in the benchmark reports. As said, this is mainly due to the lower annual volumes, the geographically distributed sources and the longer distances.

With the above conclusions, values for the cost of transport of CO_2 in the Baltic Sea region are presented. This information should be of use not only to policy makers attempting to establish economic drivers for faster CCS deployment but also for a long needed discussion about how suitable CO_2 transport business models could be conceived and implemented. A firm statement is that the investment numbers illustrate that no single industrial company can or will take the entire burden of investing in CO_2 transport systems.

The insights from this work should be followed by a discussion about “how” to move forward, rather than today’s more hesitant “if”.

Svensk sammanfattning (Swedish summary)

Visionen för projektet Bastor2 är en långsiktig utveckling av en gränsöverskridande infrastruktur för transport och lagring av koldioxid i Östersjöregionen. Av de tre huvudkomponenterna i avskiljning och lagring av koldioxid (engelska: Carbon Capture and Storage, CCS) betraktas transport-delen, som den ur teknologisk synvinkel mest mogna. Därför har det här arbetet fokuserat mer på kostnader än på teknologi. Syftet med den här rapporten är att presentera en analys, inklusive kostnader, av transport-lösningar för CO_2 och hur dessa kan komma att utvecklas över tid, till en komplett infrastruktur för större utsläppskällor, som kraftverk och processindustri, runt Östersjön.

Arbetet har tagit sin utgångspunkt i de fem största koldioxidkällorna I respektive Finland och den östra sidan av Sverige, med antagandet att dessa skulle utgöra de första CCS-projekt, som implementeras. För var och en av dessa tio koldioxidkällor, med utsläpp från 1.1 till 3.4 miljoner ton per år (här Mtpa) har den specifika kostnaden beräknats för den längsta transportsträckan, d v s från källan till lagringsplatsen. Beräkningen har gjorts för två alternativa lagringsplatser, nämligen Dalders i Östersjön och Södra Utsira i Nordsjön och för både rörlednings- och fartygs-transport. Vidare har antagits att det över tid kommer att utvecklas samlingspunkter för export av koldioxid vid dessa anläggningar och därför har transportkostnaden för den långväga transporten beräknats i steg av 1 Mtpa från 1 till 20 Mtpa. Resultatet visar alltså dels den specifika kostnaden för den första källan och dels för varje tänkbar kluster-volym, som kan bli resultatet av att fler och fler anläggningar i exportpunktens omland, som ansluts till systemet. Eftersom samtliga dessa tio utskeppningshamnar ligger vid kusten, indikerar beräkningarna också vid vilken årlig volym, som rörtransport blir mer kostnadseffektiv än fartyg.

Beräkningarna visar att fartygstransport är mindre kostsam än rörtransport, inte bara för var och av de tio första (och största) källorna utan även för de allra flesta tänkbara och relevanta klusterbildningarna i regionen. Övningen avslöjar också att de volymer, som behövs för att rörtransport ska bli konkurrenskraftig, i de allra flesta fall kräver att I stort sett alla utsläppskällor i omlandet, såväl fossila, som biogena, ansluts till klustret. I tre av de fyra analyserade klustren betyder det också att koldioxid-volymer från både svenska och finska källor behövs för att nå den nödvändiga volymen. Den specifika kostnaden för fartygstransport till Dalders för de tio utvalda källorna uppgår till mellan € 12 och € 20 per ton. Det bör noteras att teknologi för lossning av koldioxiden till havs inte finns helt utvecklad och därför kräver både viss utveckling och verifiering i pilotprojekt. Antaganden i denna rapport bygger dock på många års industrierfarenheter från motsvarande (men omvänd) verksamhet med oljetankers i Nordsjön.

Baserat på antagandet att utskeppningspunkter för CO_2 kommer att utvecklas kring de tio valda källorna, genom att ytterligare CCS-projekt i området ansluts, så har sedan kostnaderna för de nödvändiga insamlingssystemen beräknats. Dessa utgörs av landbaserade rörledningar, konstruerade för avsedda volymer och avstånd. Som ett exempel, den specifika kostnaden för den rörledning som krävs för att transportera 0.1 Mtpa CO_2 100 respektive 300 km, beräknades till € 20.0 respektive € 60.0 per ton. Motsvarande kostnad för 1 Mtpa CO_2 över samma sträckor beräknades till € 3.6 och € 9.2 per ton, vilket tydligt visar effekten på kostnaden av ökande volymer för rörledningar.

Projektet har valt att utgå ifrån att lagring sker under havsbotten, varför lagringsplatserna antas vara offshore-installationer. Den tilltänkta reservoarens lagringsvolym och injektivitet är avgörande för lagringsstrategin. För att nå högsta möjliga injekteringskapacitet och för att utnyttja så stor del av reservaren, som möjligt, så är det troligt att injektering behöver ske genom flera brunnar. Dessa borras på ett optimalt sätt med inbördes avstånd, vilket skapar ett distributionssystem på lagringsplatsen, beroende dels på lagringsbehovet (volymen) och dels på injektiviteten. För beräkningarna har antagits två alternativa värden för den senare, 0.5 och 1.0 Mtpa. Detta i sin tur resulterar i att den specifika kostnaden för distributionssystemet på lagringsplatsen, vilket i alla beräkningar antagits bestå av rörledningar, uppgår till € 10 respektive € 5 per ton.

För de fem kostnadsberäknade klustren, så utgör Oxelösund det mest reella alternativet för rörtransport. Det beror på att de i den regionen finns möjligheter att samla in en relativt stor volym CO_2, vilket i kombination med det relativt korta avståndet till Dalders gör att rörledningar kan bli mer kostnadseffektiva än fartyg. Om man antar att 13.6 Mtpa CO_2 kunde avskiljas och samlas in i den regionen, så blir den specifika kostnaden för rörtransport till Dalders respektive € 12.5 och € 15.1 per ton, för de två antagna injektivitetsvärdena.

Studien kommer fram till slutsatsen att fartygstransport för de flesta av de valda utskeppningshamnarna och klustret är den mest attraktiva transportlösningen i Östersjöregionen. Huvudorsakerna är att fartygstransport kan göras till en lägre specifik kostnad och att den kräver mindre kapital, vilket i sig innebär en lägre risk. Denna slutsats är en avvikelse från tidigare litteratur och kan kopplas till att finska och svenska koldioxidkällor är mindre och ligger mer utspridda än de huvudsakligen kraftverk, som analyserats i andra, europeiska rapporter.

Man kan även dra slutsatsen att fartygstransport skulle kunna underlätta implementering av CCS i Östersjöregionen genom att kräva lägre kapitalinvesteringar och genom sin nära nog linjära skalbarhet. Detta under förutsättningen att det utvecklats en konkurrensutsatt marknad för CO_2-transport med fartyg. Detta resonemang kan vara tillämpbart för fyra kritiska faser i implementeringen av CCS:

- Att underlätta koldioxidtransport vid karaktärisering av möjliga, geologiska lagringsplatser till havs.
- För CCS demonstrationsprojekt erbjuder fartygstransport möjligheter för flera projekt att dela kostnader och risk. Det är speciellt intressant för geologisk lagring, om transport till Nordsjön är ett alternativ, där den geologiska risken bedöms väsentligt lägre än i Östersjön.
- Efter det att ett eller flera demonstrationsprojekt visat att CCS är genomförbart i regionen, så kan fartygstransport fungera som en katalysator för en större utrullning av CCS i större skala.
- Om det skulle visa sig att berggrunden under Östersjön inte har kapacitet att ta emot den all volym, som förväntas fångas in i regionen, så är det med fartyg tekniskt möjligt att skeppa koldioxiden vidare till lagring i alternativa reservoarer. Därför kan en strategi vara att först utnyttja tillgänglig kapacitet i Östersjön för att sedan söka en alternativ lagringsplats, vilken sannolikt kan vara i Nordsjön.

Resultaten av kostnadsberäkningarna har jämförts med motsvarande i de respektive rapporterna från Zero Emission Platform (ZEP, 2011) och CO_2 Europipe (2011). Det finns stor överensstämmelse mellan de presenterade kostnadstalen för de olika transportalternativen. Dock är det viktigt att betona att de totala, specifika kostnaderna i Östersjöregionen är väsentligt högre än de som anges i de två jämförelserapporterna. Orsakerna är, som ovan nämnts, de lägre utsläppsvolymerna per anläggning, den stora geografiska spridningen på källorna samt de relativt sett längre avstånden till de valda lagringsplatserna.

Baserat på de angivna slutsatserna, så presenterar rapporten absoluta värden för transportkostnader i Östersjöregionen. Denna information bör vara av värde för beslutsfattare och makthavare, som sitter med uppgiften att utforma relevanta och effektiva styrmedel till stöd för en snabbare implementering av CCS än vad vi hittills sett. Likaså kan den stimulera en välbehövlig diskussion om hur lämpliga affärsmodeller för CO_2 transport kan utformas och sättas i verket. Det är dock tveklöst så att de samlade investeringar, som här redovisas är av en sådan storleksordning att inget enskilt företag eller CCS projekt kommer att kunna bära hela investeringen eller risken på egen hand. Kunskapen, som detta projekt presenterar borde därför leda till en diskussion om ”hur” man går vidare, snarare än dagens mer tveksamma ”om”.

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Introduction

Elforsk has organized Bastor2, (Baltic Storage of CO_2), with the overriding objective to assess the opportunities and conditions for Carbon Capture and Storage (CCS) in the Baltic Sea Region. The project is financed by the Swedish Energy Agency, the Global CCS Institute and a number of Swedish industrial and energy companies and runs from June 2012 through September 2014.

Work package five (WP5) of the project has analysed the demand for transport infrastructure for carbon dioxide and possible transport solutions based on cost estimates for different scenarios. Previous reports from Sweden and Finland describe the overall transport demand and to some extent the related generic costs. A more detailed analysis of CO_2 transport in the Baltic Sea region has not been published before, leaving a knowledge gap to be filled by the Bastor2 project.

Cost estimates in the project were benchmarked with prior reference reports available in literature. As part of the analysis, suitable transport system evolution models were discussed.

Chapter 1 explains the methodology used to estimate transport cost, presents the five largest emission sources in Finland and Sweden, respectively and provides a description of the different parts of the transport system.

Chapter 2 explains how the cost estimates were made and under which assumptions, describes the main cost elements and gives some key definitions.

Chapter 3 is a discussion about the decision making process for CCS deployment in general and in the Baltic Sea region in particular and how the early transport systems could evolve over time.

Chapter 4 presents the actual results of the cost estimates for part systems and for four complete clusters and illustrates the specific cost impact on pipelines as a function of utilization rate.

Chapter 5 makes a comparison between this report and the two main reference studies on CO_2 transport in Europe, the Zero Emission Platform (ZEP, 2011) and CO_2 Europipe (2010).

Chapter 6 discusses arguments for (and against) pipeline and ship transport respectively, as well as onshore and offshore pipelines in the Baltic Sea region.

Chapter 7 presents the conclusions, including alignment of results, comparisons with continental Europe, shipping as an attractive alternative and pipelines in south Sweden.

The reference list includes all reports referred to and other sources of information used in this work package.

1 Methodology

This report analyses large-scale transport of CO_2 in the Baltic Sea region, both by pipeline and by ship. Much focus is devoted to analysing development and cost for transportation systems connecting clusters of emission sources. Combined Finnish-Swedish as well as systems only serving Swedish emission sources are analysed and discussed. Many of the sources situated around the Baltic Sea, particularly on the Swedish side, emit biogenic CO_2 emissions. Biogenic sources have been included in the various transport schemes developed and discussed below partly because they are needed to create volumes high enough to make pipeline transport less costly than ship, but partly also because biogenic CCS, or BECCS, is becoming increasingly interesting as a plausible mitigation option to meet very strict emission reduction targets and to perhaps neutralize emissions from sectors where large reduction cuts are difficult to realize or take long time to realize.

In this report some terms are used to describe the transport system:

Buffer storage	Intermediate storage of liquid CO_2 for ship transport, either at export terminal or at storage location
Carbon dioxide	The greenhouse gas being the objective of CCS, term used intertwined with CO_2, its chemical denomination
Cluster	Combination of (volumes from) adjacent emission sources
Distribution system	A system of sea-bed installations with well templates and short pipelines for distribution of CO_2 on a storage location
Feeder	Pipeline for transport of CO_2 from individual source(s) to hub
Hub	Collection point for CO_2 from more than one source, with facilities for either ship loading or being the point of departure for spine pipeline. Also mentioned as export terminal or export point
Spine	The long haul transport from individual source or hub to storage location
Storage	Geological storage of CO_2

The approach has been to first identify the ten largest, single sources of carbon dioxide emissions, which could likely become first movers in deploying Carbon Capture and Storage, CCS, in Finland and Sweden. Finland has been included since there is a good potential for combined cross-border transport and storage systems around the Baltic Sea and since Bastor2 has been collaborating closely with the Finnish CCS program, CCSP. It has furthermore been assumed that regional CO_2-hubs will evolve at the sites of the ten selected sources collecting captured CO_2 from other potential capture plants in the region. For all sources it has been assumed a capture rate corresponding to 85% of the year 2010 CO_2-emissions (see Table 1) which may seem overly optimistic for some of the sites but a detailed site analysis to assess relevant capture rates at each individual site is beyond the scope of this report. The ten selected sources and their CO_2 emissions in 2010 along with assumed capture volume are shown in Table 1 (see also Figure 1). At the time when CCS is realized the characteristics of the emission sources given in Table 1 may obviously be different or some may not exist at all. Thus, this work assumes the same industry structure as present.

Table 1 Assumed first movers/hubs for development of CCS in Finland and Sweden

First movers/ hubs	Location	Sector	CO_2-emissions (t/a)	Captured CO_2 (t/a)
Rautaruukki	Raahe	Iron and steel	3 970 000	3 374 500
Neste Oil	Porvo	Oil refinery	2 930 000	2 490 500
Fortum	Meri-Pori	Power & heat	2 814 000	2 391 900
Vaskiluoto 2	Vaasa	Power & heat	1 330 000	1 130 500
Fortum	Turku	Power & heat	1 640 000	1 394 000
SSAB	Oxelösund	Iron and steel	2 170 000	1 844 500
LUKAB	Luleå	Power & heat	1 990 000	1 691 500
Cementa	Slite, Gotland	Cement	1 430 000	1 215 500
Korsnäsverken	Gävle	Pulp and paper	1 330 000	1 130 500
M-real	Husum	Pulp and paper	1 690 000	1 436 500

Emissions from Korsnäsverken in Gävle and M-Real's facility in Husum are almost entirely biogenic while emissions from the other eight plants listed in Table 1 are entirely fossil based apart from the 40 kts bio-based emissions from Cementas plant on Gotland.

After the selection of first movers and the location of the hubs, the battery limits for the transport system were defined and the different logistic chains were described. All transport systems have been divided into three parts (see Section 1.1 for a detailed description); 1) the onshore collection system (feeders), 2) the main bulk transport system (the spine) which may be onshore and/or offshore and by pipeline or by ship 3) the distribution system at the storage site which is entirely offshore. Transport cost has been calculated for the part systems isolated as well as for complete systems comprising all three parts.

Storage capacity and injectivity, i.e. injection rate, are key parameters for a storage site and also for the transport system at the storage site.

Two potential storage reservoirs and location of specific injection wells have been selected as end points for all transport systems, namely the Dalders structure southeast of Gotland in the Baltic Sea and the southern part of the Utsira aquifer in the North Sea. The Dalders structure was selected since the project has had access to significant volumes of high quality geological data on this structure while the southern part of the Utsira aquifer was selected partly to have an optional fall back injection site and partly since it has been well characterized with CO_2 injection for nearly two decades from the Sleipner field,. The distance between the selected injection point in Dalders and Utsira is around 1,400 km[2]. There are potential storage reservoirs located closer to the Dalders structure than Utsira, for instance the Gassum structure in Skagerrak and the Hanstholm aquifer off Jyllands northwest coast, but storage capacity and injectivity is uncertain in these reservoirs while at the same time CO_2 has been injected into Utsira since 1996 and the aquifer is considered as a prime reservoir for storage of CO_2. Figure 1 shows the selected hubs listed in Table 1 along with some of the potential storage sites in the region. Observe that the size and spatial distribution of the storage sites are illustrative only.

For all pipeline cost calculations in this report it has been assumed that plateau flow is reached from day one of operation. This is however a highly unlikely development, why the effect of underutilised pipelines on cost, so-called ramp-up, is being analysed and discussed in a separate section.

All transport distances have been measured as a straight line in a Geographical Information System (GIS) upon which 20% has been added to onshore distances and 10% to offshore distances to reflect potential deviations from such a route in reality. No further considerations have been taken with regard to the effect of topography and water crossings on the cost unless explicitly stated.

[2] The extra distance of 1,400 km to Utsira is measured from the Dalders injection site. For some of the systems described below another route than via the injection site at Dalders was selected, leading to slightly shorter additional transport distance.

Figure 1: Selected "first movers", location of hubs and storage sites

Pipeline transport cost has been calculated using a modified cost equation from IEA (2005) benchmarked against cost for specific pipelines provided by ZEP (2011). The modifications to the applied cost equation from IEA have been done after talks with the oil and gas industry on, among other things, cost for on- and offshore pipeline connections and subsea equipment. The ship transport cost has been estimated by using a proprietary model, based on industry cost models for hydrocarbon gas transport.

Figure 2 illustrates the workflow applied in this work.

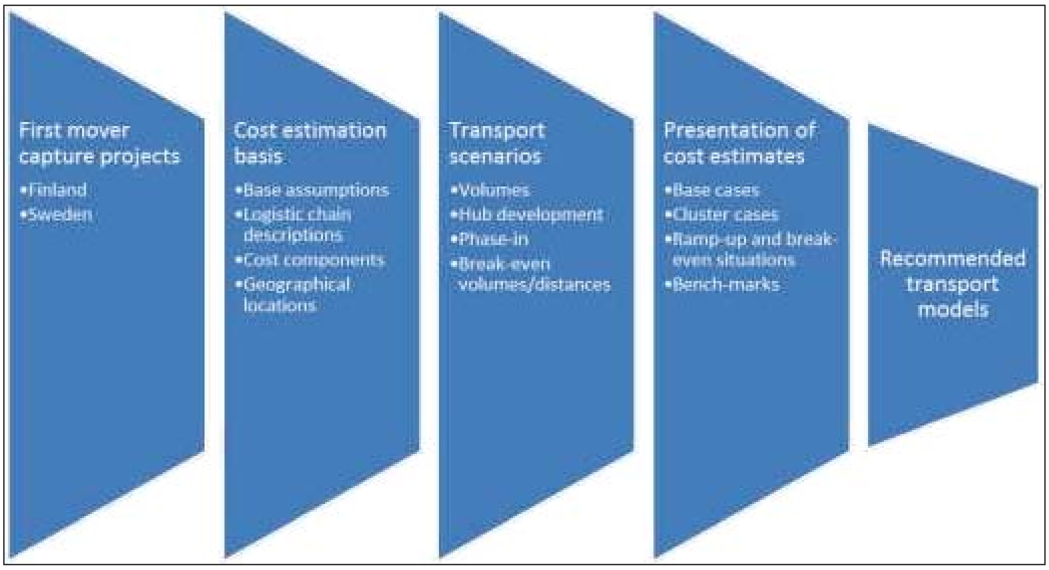

Figure 2: Illustration of the work flow applied in this paper

1.1 General description of the transport system

Large volumes of CO_2 will most likely be transported by pipeline or, if possible, by ship or by a combination of the two. Onshore CO_2 pipelines have existed in the US since the 1970s bringing CO_2 either from natural or anthropogenic sources to oil fields for enhanced oil recovery, so-called EOR. In the Barents Sea in Norway, Statoil has operated a 150 km long offshore CO_2 pipeline since 2008. Pipeline transport is usually characterised as a rigid, inflexible transport mode but also as having considerable scale effect with regard to cost, i.e. significant cost reductions may be achieved by increasing the transport volume. Given that most of the large CO_2 emission sources in Sweden and Finland are located along the coast, this provides Sweden (and Finland) with favourable conditions for scaling up its CO_2 transport system in the least costly way, by first utilising ship until volumes have reached levels where pipeline transport becomes the more cost efficient transport mode.

As mentioned above, in this report all transport systems have been divided into three parts; onshore pipelines (feeders) comprising the collection system, an onshore and/or an offshore bulk transport system by ship or by pipeline (the spine) and an offshore distribution system at the storage site. Figure 3 shows the complete transport system divided into its main components.

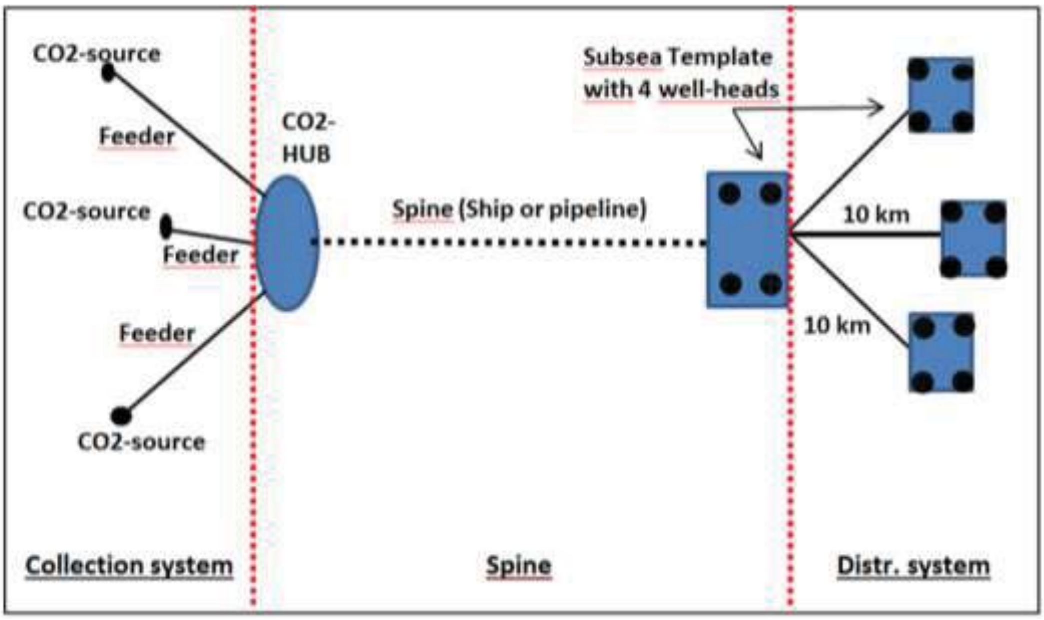

Figure 3 A complete transport system

Comprising an onshore collection system, an onshore or offshore spine from the regional CO_2-hub to the injection site and an offshore distribution system at the storage site.

The report analyses each part of the transport system separately as well as how the separate systems can be integrated into a complete system.

This approach has been chosen since 1) it appears speculative to evaluate the geographical distribution over time of multiple capture sites, 2) the sources both on the Finnish and Swedish side of the Baltic Sea are located so close to each other that numerous potential combinations of clusters may evolve over time, 3) the collection and distribution systems are assumed to constitute a relatively modest part of total transport cost (as verified in Section 5), 4) the collection system is assumed to comprise more or less standard volumes over standard distances, e.g. 100 kt to 1 Mt transported onshore over 10 to 100 km, 5) the collection and distribution systems will of course be identical when comparing ship and pipeline transport and finally 6) any distribution system will be a function of well/reservoir injectivity and transported volume and cost will therefore depend only marginally on the other parts of the system. Thus, cost estimates for each of the three sub systems may be combined to provide relatively accurate cost estimates for most potential transport system in the region. The main disadvantage of this approach is that in a pipeline system, the various pipeline segments will affect each other leading to a different selection of optimal pipeline diameters, number of boosters and pressure levels. However, this is assumed to have a relatively marginal effect on cost and the spine will anyway account for the bulk of the cost in most of the systems along the Baltic Sea due to the long transport distances (as is actually verified in Section 4).

1.1 Pipeline transport of CO_2

Transport of large volumes of CO_2 by pipeline is likely to take place at elevated pressures thus reducing the volume and raising the density of the CO_2. In general it is expected that the CO_2 will have a pressure above its critical pressure, i.e. above 73.8 bar when transported by pipeline. However, it may also be transported as a dense liquid at around 70 bars at ambient temperatures experienced in the Nordic countries. In this work it has been assumed a minimum pressure of 70 bar and a maximum onshore pressure of 110 bar. Offshore pressure is based on a minimum pressure of 70 bar upon arrival at the storage site assuming no offshore boosters. Temperature has been set to between 0 and 20°C to ascertain one-phase flow. It is furthermore assumed that the CO_2 has been dehydrated containing less than 500 ppm water (% by volume) and that it has a purity of at least 99%. The pipelines are assumed to be made of carbon-manganese steel applying American Petroleum Institute (API) specification 5L. This pipeline standard is graded with an X and followed by a number that indicates their specific minimum yield strength in kilo-pounds per square inch (kpsi, 1 kpsi = 0.0703 kg/cm2). In this study it has been applied pipelines with API 5L X70 steel.

The analysis of the pipeline transport systems starts from the ten selected hubs; five in Finland and five in Sweden (see Table 1 and Figure 1) covering each of the three part systems, i.e. the feeders, the spine and the distribution system. All transport systems are assumed to end at the selected storage sites. Below, each of the three part systems is described in more detail.

1.2 Collection systems - Feeders

The collection system, or the feeders, refers to pipelines from potential capture plants located in the vicinity of the ten selected hubs thus forming the basis for a cluster development. In the analysis below all potential capture plants have been assumed to connect to the closest located hub unless otherwise stated explicitly. All feeders are assumed to start at the capture plant after compression up to the critical pressure, i.e. up to 73.8 bar, and to terminate at the hub. Only onshore feeders have been considered in part since they generally are assumed to be less costly than corresponding offshore feeders and in part since the location of the capture plant in many cases excludes an offshore option.

In the analysis below, cost of feeders has been analysed in two ways; first a generic approach was chosen assuming standard volumes being transported over standard distances, e.g. 100 to 1700 kts over 50 to 500 km. The aim of this part of the work was to cover most of the potential feeders that may develop in the region. In addition, cost of feeders was calculated specifically as part of a complete pipeline system covering clusters of CO_2 sources.

1.3 Bulk transport - Spine

The spine is the main part of the transport system taking the collected CO_2 from the hub to the storage site either by pipeline or by ship. The spine is assumed to start at the hub and since both storage sites applied in this work are located offshore, to terminate at the storage site in a subsea template with four well heads and a control cable (a so-called umbilical control cable[3]). Thus, there is no distribution system if four injection wells are sufficient to inject the transported volume. In the Baltic Sea region the spine may be entirely offshore or part onshore and part offshore.

1.3.1 Pipelines

As mentioned above, the spine starts at the selected hub taking the CO_2 to the selected injection points at Dalders and Utsira. The analysis below covers spine pipelines that are part onshore and part offshore as well as entirely offshore spines. In the latter case it has been assumed that there is no boosting of the pressure after the CO_2 has left the hub, i.e. the pressure has been raised at the hub to sufficient high levels so that the pressure is at least 70 bar upon arrival at the injection site. An alternative approach, in particular for transport to Utsira, could be to direct the pipeline onshore along the route (e.g. on Gotland) for additional boosting.
Spines have been analysed in four ways;

1) As a stand-alone offshore spine transporting only the CO_2 captured at each of the ten selected capture sites individually (see Table 1). The analysis covers both pipeline and ship spine.
2) As a stand-alone offshore spine from each of the ten selected hubs raising the annual transport volume from 1 Mt to 20 Mt (in steps of 1 Mt). The analysis covers both pipeline and ship spine.
3) Offshore as part of a complete transport system covering five specific clusters in Sweden and three in Finland. Three of the

[3] An umbilical control system is a bundled arrangement of tubing, piping and/or electrical conductors in an armored sheath that is installed from a host facility to the subsea injection system equipment. It is used to for transmitting control fluid and or electrical current necessary to control the functions of subsea injection and safety equipment

Swedish clusters are connected to the three Finnish clusters through an offshore subsea Pipeline End Module (PLEM) and tie-ins (see Figure 3). The remaining two Swedish clusters are assumed to evolve around Oxelösund.

4) Onshore and offshore semi-spines connecting CO_2 collected at each of the five selected Swedish hubs.

Points 1) and 2) compare cost of the ship spine with corresponding cost for the pipeline spine yielding the least costly transport mode for the selected source itself, the least costly transport mode for volumes between 1 to 20 Mt per year and finally, the volume required and the associated cost for pipeline to be the least costly transport mode.

As mentioned in point 3) we have also calculated cost for three cluster systems in Finland and three cluster systems in Sweden where a cluster on the Finnish side of the Baltic Sea is assumed to combine offshore with a cluster on the Swedish side of the Baltic Sea to form one, single large spine to the storage site. This has been done for hubs being developed at Raahe and Luleå, at Husum and Vasa and at Korsnäs and Meri-Pori respectively. Offshore pipelines are assumed to end in a Pipeline End Module (PLEM) before being tied in and connected to a new larger pipeline as illustrated in Figure 4.

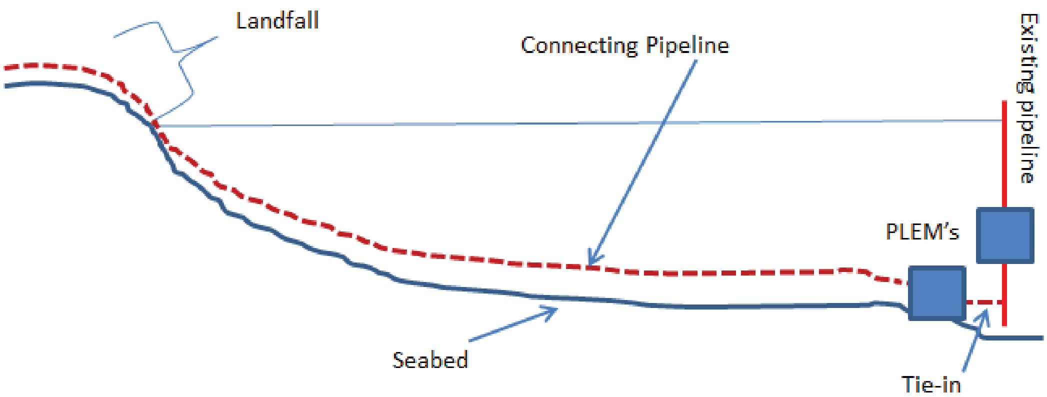

Figure 4 Illustration of an offshore connection point for two spines

(Figure reprinted with the courtesy of Nils Henrik Eldrup, Tel-Tek)

In addition to the three combined Finnish-Swedish transport systems we calculated cost for two altogether Swedish cluster systems being developed at Oxelösund as well as for an onshore semi-spine in Sweden stretching from Luleå in the north to Oxelösund in the south assuming the various hubs are connected via an onshore pipeline before the system moves offshore at Oxelösund and via Gotland to the storage site.

1.3.2 Ships

Figure 5 illustrates the main components in a ship logistic system.

Figure 5 Ship transport system scope

Following the capture process, with the gas compressed to the critical pressure of 73.8 bar, a liquefaction process will condition the gas to become liquid at -55°C and medium pressure 8 bara. This could be considered the optimal state of the carbon dioxide for the ship logistic chain. In this state the CO_2 has high density at 1.15 t/m^3 which means better, overall transport economy than at other pressure/temperature combinations. In this study it has not been taken into account the possibility of transporting the gas in a compressed mode as there is no track record for this technology in marine transport.

Transport by ship obviously results in a batch type of transportation with vessels shuttling back and forth between the export hub and the geological storage location. Thus, the injection process at the storage site is here assumed to be intermittent in the case of ship transport. Therefore, onshore buffer storage has been included in the logistic chain, dimensioned to a size equal to the ship size to allow the capture and liquefaction processes to continuously produce liquid carbon dioxide while the ship is in transit between the capture and storage sites and while loading from the buffer storage. Buffer storage tank/s/ and liquid pump are assumed to be located close to the quay side where the loading equipment ensures an automated loading process when the ship connects in port.

The design and operation of CO_2 carriers will be similar to that of semi-refrigerated carriers for liquefied petroleum gases (LPG). As for all liquid shipping, the larger the vessel, the lower the unit cost, why the total volume should be maximized in the logistics schedule. Typical LPG carriers range from around 10 000 m^3 up to around 40 000 m^3 which with today's technology is considered the maximum, economical size for semi-pressurised tanks. In order to reduce the costs of ships and storage tanks, especially the thickness of the tanks' walls, it is preferable to operate at the lowest possible pressure which is as close to the triple point of -56.6°C/5.2 bara as is practically feasible. While in transit, heat ingress through the tank walls will cause the CO_2 temperature to increase slowly and as a consequence a minor pressure increase (less than 0.1 bara per day), why the tanks are assumed to be designed for 8-9 bara, which will also be the maximum delivery pressure. As the storage locations are assumed to be offshore, the ships should be designed with systems for dynamic positioning and for submerged turret discharge (compare STL). Discharge of CO_2 from gas tankers offshore has never been implemented, why the technical solutions for the discharge of cold liquid carbon dioxide needs technological verification, especially in order to avoid the formation of ice in and/or around the pipes and flexible hoses used. The techniques and procedures for manoeuvring and connecting to the turret to stay on station for longer periods of time have been successively developed and refined for offshore supply vessels in the oil industry and for the oil shuttle vessels, e g in the North Sea. For this type of smaller gas tankers though, the solutions need to be implemented, tested and verified to hold the required level of operability under the given sea and weather conditions. Given the long oil field offshore experience, these challenges have been deemed acceptable and to be covered by the capital expenditure included in the cost estimates of this report.

The offshore discharge procedure in these cost estimates is assumed to be slow, which implies that the ship stays on station for the time period it takes to re-gasify the CO_2 to the conditions applicable for the selected storage location. This is represented with the gas processing vessel in Figure 5 (“Regasification”). An alternative design would be for the shuttle vessel to discharge liquid CO_2 at a higher rate into the offshore buffer storage from where the regasification process would be performed. The advantage would then be that the ship would stay shorter periods at the offshore location, thereby both reducing exposure to harsh sea and weather conditions and liberating the ship to return to the export point to load the next batch of carbon dioxide. The design and operational complexity would probably be lower in the first alternative why that has become the model chosen for the cost estimates in this project.

Ice conditions in the Bothnia Bay must in real projects be taken into consideration, both for ship design and when calculating total round trip times for the logistical schedule. Ships with higher ice class are less dependent on wintertime convoys and pay lower Fairway Dues than regular design ships. The vessel’s ice class impacts the total steel weight and the dimensioning of critical components as well as it requires higher installed propulsion power. In short, ice conditions increase both capital and operating cost. For the cost estimates in this study however, the added specific costs have not been taken account of, since the absolute numbers were found to be well within the total error margins applied.

As an example, figure 6 shows the ice (red) coverage situation in mid-March 2007:

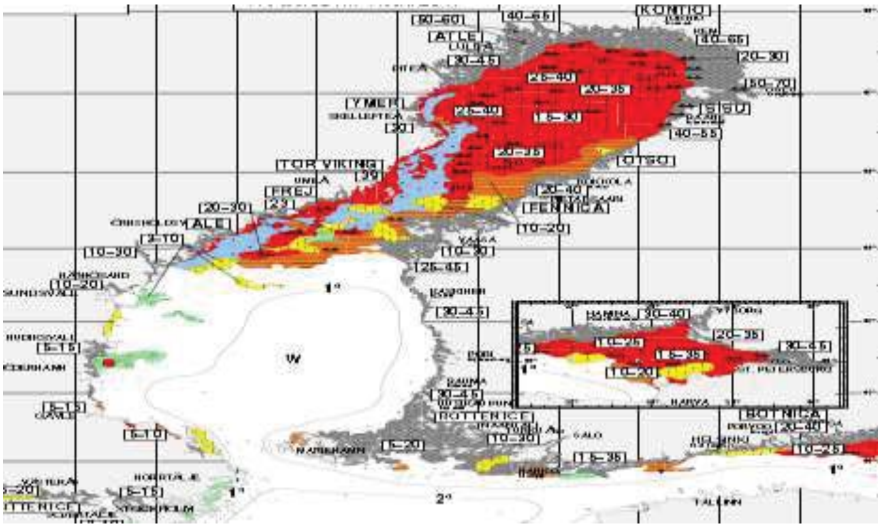

Figure 6 Ice conditions (red) in the Bothnia Bay mid-March 2007

For a more detailed analysis, the logistical schedule would need to be amended, to take into account an average shipping distance of 200 nautical miles in ice. This in turn, means that chiefly Luleå and Raahe cost wise would be affected by additional shipping costs due to ice.

1.4 Distribution system (at the storage site)

It has been assumed that the CO_2 has a minimum pressure of 70 bar upon arrival at the last injection site. Since the spine is assumed to terminate in a 4-slot subsea template with four well heads, distribution pipelines will be added to the transport system only if more than four injection wells are required. Each distribution line is assumed to have a length of 10 km and, as the spine, terminate in a four-slot subsea template with four well heads. Thus the number of distribution lines will depend on the number of injection wells which in turn will depend on reservoir and well injectivity and total volume to be injected. In this work, injection rates of 0.5 and 1.0 Mtpa per well have been applied. A control cable is assumed to connect the first template with a land-based control station at Gotland’s south coast or, in the case of transport to Utsira, with a nearby platform. Additionally, it has been assumed a 10 km control cable between each template. Figure 7 shows a potential distribution system and its link to the spine and the cost calculations for the spine.

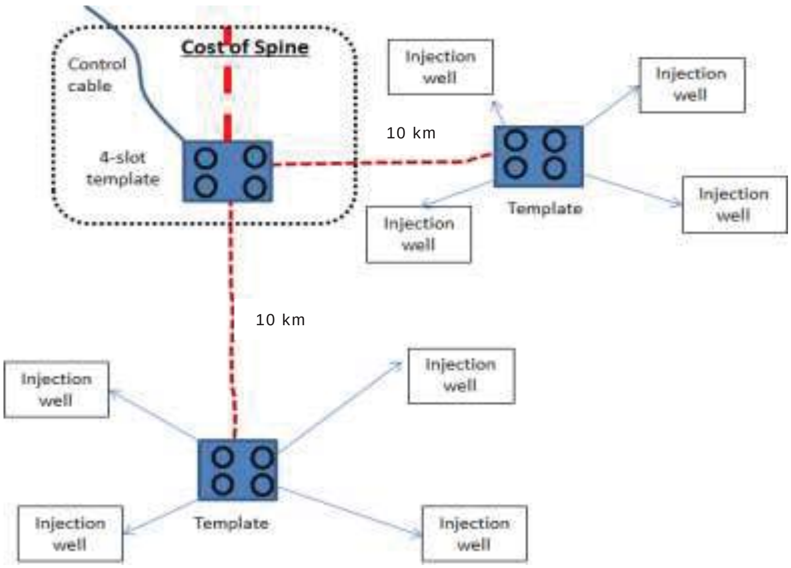

Figure 7 The transport (distribution) system at the storage site

(Figure reprinted with the courtesy of Nils Henrik Eldrup, Tel-Tek.)

Starting from the first injection site, distribution lines at Dalders (cf. Figure 3) are assumed to go in a north-eastward direction towards the Bay of Riga while at Utsira the distribution lines are assumed to go in a northern direction from the first injection point. Cost for water producers to manage pressure increase within the reservoir has not been included. Figure 7 shows the assumed disposition at the storage site illustrating what has been included in the cost of the spine (within the black dotted rectangle) and the distribution system respectively.

2 Basis for cost estimation

2.1 Main cost elements

Table 2 lists the main economic parameters applied in this work.

Table 2: Main economic parameters used in this work

Parameter	*Assumption*
Discounting method	Annuities: All annual costs added and divided by the accumulated, injected CO_2-volume
Technical lifetime	Forty-one years
Economic lifetime	Twenty years
WACC	Weighted average cost of capital, 8%
Cost level year	2012
Operating profile	8 000 hours per year
Currency exchange rates	Year 2012
Cost of electricity	0.11 €/kWh

Table 3 lists main capital cost items for transport by on- and offshore pipelines and by ship (see also Figure 3). Most of the pipeline cost data in Table 3 comes from discussions with the oil and gas industry during spring 2014. Costs for design, construction and commissioning of pipelines are included as capital cost items.

Table 3: Main capital cost items

Module	***Pipe/ Ship***	***Cost item***	***Cost estimate***
Collection			
		Pipeline CAPEX typical local, onshore pipeline €[1]/km	484,000
		Onshore booster, €	15,000,000
Spine			
	Pipe		
		Pipeline CAPEX typical offshore line pipe, €[2]/km	1,580,000
		Offshore Pipeline End Module (PLEM), €[3]	40,000,000
	Ship		
		Gas tanker 10 000 m^3	36 000 USD
		Onshore buffer storage	1 000 €/m^3
		Offshore discharge terminal (1 m t p a)	25 000 k€
Distribution			
		Subsea four-slot template with four well heads, €[4]	118,000,000
		Umbilical (control) cable €[3]/km	1,620,000
		Local offshore pipeline €/km[5]	34,000,000

Notes:
1: 1 million ton transported over 100 km
2: 10 Mton over 660 km
3: Based on 2012 average exchange rate (1 € = 7,4744 NOK)
4: Based on 2012 average exchange rate (1 € = 1.2848 USD)
5: 4 Mton over 10 km.

2.2 Basis for pipeline cost estimation

In this report the design of pipeline systems and calculation of its associated cost starts with a modified version of IEA's pipeline cost equation (IEA 2002, 2005) being applied by Chalmers pipeline design and cost model. The modifications to the IEA equation refer mainly to cost covering installation of subsea equipment such as Pipeline End Modules (PLEM) and templates with well heads and associated control equipment. The cost for these additions has been provided through discussions with the oil and gas industry. The selection of IEA (2005) cost equation instead of later versions of the same has been based on benchmarking cost derived from various IEA pipeline cost equations against cost for specific CO_2 pipelines in ZEP (2011). All costs have been adjusted to 3rd quarter 2012 utilising IHS Upstream Capital Cost Index (UCCI, IHS 2014).

Modelling pipeline transport of CO_2 is characterised by the relationship between the pipelines diameter and the pressure of the CO_2, i.e. the larger the diameter the lower the pressure loss for any given CO_2-volume (expressed as mass flow) over a given transport distance. Chalmers pipeline design and cost model is formulated as an optimisation problem where the pipeline diameters and booster station locations are determined by the model to achieve the lowest possible total cost of a transport system without violating any physical constraints. The optimisation is an integer problem which means that the solution may change substantially due to relatively small changes in input parameters.

In the model maximum mass flow velocity has been set to 2 m/s while maximum pipeline diameter has been set to 48 inches. The mass flow is based on 85% capture rate on year 2010 emissions divided over 8,000 hours per year. It has furthermore been assumed that the CO_2 has been dehydrated containing less than 500 ppm water (% by volume) and that it has a purity of at least 99%. For pipes, tanks and other main components it has been assumed use of carbon-manganese steel. Cost of electricity has been set to € 0.11/kWh.

All pipelines and individual pipeline segments have been designed based on plateau flow already from start of operation implying that all sources in the system connect to the network in the same year which however is very unlikely. On the other hand it appears speculative to decide the geographical distribution of CO_2-flow over time, i.e. to decide which capture plants will be connected to a system at any particular time. Thus, the work also analyses the effect on cost from underutilisation of pipelines to illustrate risk taking in connection with build-up of a pipeline transport system.

As mentioned above all transport distances have been measured in GIS (Geographical Information System) after which 20% has been added to the distance for onshore systems and 10% for offshore systems, to allow for routing complexities. No other considerations have been taken with regard to for instance water crossings or topography and corresponding pressure adjustments along the various pipeline routes. Neither has pipeline wall thickness been changed for offshore pipelines as a function of outside pressure (at 500 m depth the outside pressure of the pipeline will be around 50 bar).

Also as mentioned above it has been assumed that the transport system starts at the capture site after compression up to the critical pressure (73.8 bars), i.e. cost for initial compression is not included in the transport cost reported here. Furthermore, minimum and maximum onshore pressure has been set to 70 and 110 bar respectively while offshore pressure is boosted at the CO_2-hub to sufficient level to ensure a minimum pressure of 70 bar upon arrival at the last injection well, i.e. there is no intermediate boosting of the CO_2 in the spine although this might be the least costly solution for CO_2 being transported all the way to Utsira (e.g. a booster station on Gotland).

To connect offshore pipelines the cost of a so-called PLEM (Pipeline End Module) at the end of each pipeline segment and a tie-in has been added to the system cost (see Figure 4).

At the storage site, as described in Section 1, the spine is assumed to terminate in a subsea template and a control cable (see Figure 7) to a land based control station (at Dalders in the Baltic Sea) or to a control station located on a platform in the vicinity of the injection site (at Utsira in the North Sea). The distance to a land based control station on Gotland has been estimated to 127 km while the distance to a possible platform in the North Sea has been set to 50 km. Well injectivity has been set to 0.5 and 1.0 Mt per year and well. If four wells are sufficient to inject all the transported CO_2-volume then the transport system terminates at the first and only subsea template without a dedicated distribution system. In other words, a distribution system is only developed if more than 4 injection wells are required to inject the transported CO_2. The distribution system consists of 10 km distribution lines connected to the spine, each ending in a four-slot subsea template with four well heads. The templates in the distribution system are controlled via 10 km control cables going back to the first template. The number of (10 km) distribution lines, each ending in subsea templates will thus depend on total annual volume of CO_2 to be injected and well injectivity.

Annual cost comprises CAPEX (capital expenditure) and OPEX (operating expenditure). OPEX for pipelines was set to 3% per year of total investments while OPEX pumps was set to 5% per year of total investments plus the cost of electricity set to € 0.11/kWh. To calculate specific cost of transport (€/tCO_2) the annuity method was used, i e all annual costs are discounted back to year zero and thereafter added and divided by the accumulated volume of CO_2, injected over the project lifetime. System (technical) lifetime (years with transport and injection) has been assumed to be 2020-2060, i.e. 41 years of which economical lifetime is 20 years (i.e. 20 years depreciation to zero) of which 2 years for construction. The technical lifetime is reflected in the calculation of maintenance costs.

2.3 Basis for ship cost estimation

The estimates of ship transport cost were made with the base assumptions described in the following section, organized in sequence along the physical supply chain from export port to storage location. All cost data is based on information from the industry but without having requested specific quotations from suppliers.

The ship system cost calculation is based on the availability of suitable port facilities, where it is assumed that there is space available for the additional installations for the CO_2 export. This means that no capital investment has been included for general port facilities. Instead a market price port fee is included in the operating cost for the shuttle vessels. The onshore buffer storage for the cold, liquid and semi-pressurised CO_2 is capital intensive. Therefore the standard unit cost of € 1 000/m^3 has been used for the cost of a floating storage (barge), permanently moored in the export port. Should onshore buffer storage be required, costs are expected to be higher. Capital investment for the loading equipment on the quayside like liquid pumps, flexible hoses and loading arms has been included.

The cost for the ship transport system has been modelled in a logical sequence based on the respective transport capacity requirements which provides the basis for the daily volume transport assignment. The next step was to establish base data about the sailing route, distances, fairways, port fees etc. Ice conditions have been coarsely estimated to increase total spine cost between 2 and 4 percent but this is only a first estimate and it was beyond the scope of this study to enter into any detail. It is also safely within the error margin for many of the main cost elements in this work, why it was not included in the cost tables below. With the transit speed fixed at 14 knots the transit time is established. To complete the round trip time calculation, assumptions for loading and discharge times were made. For shuttle vessel operations it is beneficial to operate at reasonably fixed times of the day. Loading time has been fixed at twelve hours (as a function of liquid pump capacity) and discharge time at thirty six hours (as a function of gas heating capacity offshore). Loading and discharge times have been fixed, regardless of ship size. Customary sea margins have been included. The total round trip time also includes other elements like manoeuvring time at port and ditto at the offshore location, which in itself involves some uncertainty depending on weather and sea conditions.

With the daily volume assignment and the total turn-over time the ship transport capacity was calculated which then formed the basis for the theoretical ship design for the transport task in question. The proprietary calculation model was built to optimize the ship size after the volume requirement why the ship will theoretically always operate at full capacity. Given the maximum ship size of 40 000 m^3, the result for some of the ten earlier projects at the greater distances and equally for some of the clusters, was that two or more ships were required to solve the logistical assignment.

For the shipping capital costs, it has been assumed that all vessel capacity will be new built for the purpose of the designated CCS project. Basic ship design follows current best available technology for LPG carriers with the required modifications for the assignment to transport liquid carbon dioxide. Consequently the baseline new-build ship cost is the cost for a 10 000 m^3 LPG tanker which price was obtained from the current market prices (2011) at USD 36 000 000, built at a ship yard in South Korea or China. The costs added to this baseline for the ship construction, pertain to the slightly higher maximum allowable tank pressure, to the dynamic positioning system (DPS) and to the hull being modified for connection to the submerged turret loading system STL to enable discharge offshore. Finally, the ship capital cost has been scaled along with the volume requirements for each of the calculated transport assignments up to the maximum size of 40 000 m^3. The model assumes that the ship will be used on the project for its lifetime and leave no residual value.

The main ship operating expenditures (OPEX) comprise fuel, maintenance, ship crew and port fees. For fuel costs, these are based on liquefied natural gas (LNG) at a price level similar to the current market prices for marine diesel fuel (MDO). Maintenance has been estimated as a percentage of the ship's capital costs and crew costs are based on crewing from within the EU.

For costs of shipping to be at all comparable to the pipeline transport costs, all auxiliary equipment has been cost estimated and added to the shuttle shipping costs as laid out above. These elements then include a standard charge of an additional € 5.00 per ton CO_2 for the liquefaction process, costs for export point buffer storage and loading equipment and storage location installations like STL and gas processing equipment.

3 Transport scenario development

This section discusses the decision making process for installation of CCS in general and at individual sites in the Baltic Sea region and what will be required for development of CO_2 clusters situated around the ten selected sources.

Firstly, installation of capture equipment will require investments of billions of Euros and for many process industries, applying CO_2 capture requires that the manufacturing process has to be changed which will further add to the cost. It is likely that any such investment including timing of the investment will be based on corporate strategies, i.e. any company will have an overall corporate strategy with respect to how, where and when it chooses to achieve emission reductions at their different sites. For instance Heidelberg Cement's Nordic branch has a vision to reach zero CO_2 emissions in 2030 applying, among other technologies, CCS starting already in 2018. Heidelberg's plant in Brevik, Norway, is currently testing different capture technologies at a pilot plant (Heidelberg 2014).

Secondly, the site specific cost of the entire CCS system (capture + transport + storage) relative to other mitigation options at the same site will be an important driver. Cost of capture constitutes the largest part of total CCS system cost, estimated for instance by ZEP (2011) to account for between 78 and 91% of total system cost for single systems (capture from coal power plant, storage in onshore aquifer) and to between 58 and 72% for cluster systems (capture from coal and gas power plants, storage in offshore aquifers). Corresponding shares for transport and storage cost were between 5 and 6% for transport and between 3 to 18% for storage in the first case (single source) and between 14 to 18% for transport and between 10 and 28% for storage in the second case (cluster system). Although the cost calculated by ZEP (2011) depends on a large number of factors and refers to capture from power plants and thus is not directly comparable to Nordic conditions, the overall conclusion that capture constitutes the largest share of total CCS system cost should be valid (capture from industry sources will usually be more costly than capture from power plants since industry plant emissions often are spread over a large number of individual sources). Thus, it can be concluded that large emitters situated relatively close to relevant storage sites will be the first movers in a CO_2 cluster development but still dependent on individual corporate strategies. Likewise, it can be concluded that medium sized emitters will connect to a network provided sufficient incentives are in place and according to corporate decisions. No conclusions can be made with regard to when individual sources will connect to a potential transport network apart from that it will require proper incentives and again that a decision will be based on individual corporate strategies. Investment decisions for transport and storage may be seen as infrastructure development and therefore be made in private-public collaboration. Here the formation of cluster partnerships could have a catalysing effect on the investment decision process.

Thirdly, the element of risk is a very important factor with regard to build-up of cluster CCS systems. It can be envisaged a situation where some or several large CO_2-sources located relatively close to each other decide to collaborate on a CCS scheme to share cost and minimize risk. In such a situation they may collaborate on a common large scale transport system and the cost associated with certification and use of relevant storage and injection capacity. The same sources may also be able to more easily accommodate inclusion of additional sources into the scheme simply because capacity utilisation in the scheme (both with regard to transport and storage) is relatively close to maximum utilisation anyway. However, if the decision to apply CCS is taken individually at a corporate or company level, there is instead a risk that we will see the build-up of several individual source-sink systems, each with little spare capacity to accommodate additional sources. The reason for this is that the cost for underutilisation of pipelines is very sensitive to time and that the cost for offshore drilling, which most certainly will be required to certify offshore storage/injection capacity, is very high. In the latter case, it is suggested that the larger the storage capacity/injection capacity that is required, the more costly the certification of the reservoir.

Based on the above, the ten largest emission sources in the region were selected as the first movers (five in each Finland and Sweden) and these sites were also chosen as possible localisation of regional hubs. In the Baltic Sea region there is a clear advantage that most sources are located along the coastline enabling the captured volumes to be transported by ship until volumes have reached the level where pipeline transport becomes less costly than shipping (see for instance Table 4 and Figure 8).

Also based on the above, no considerations have been made with respect to timing for individual sources, i.e. for most calculations it has been assumed that all sources have been connected to the system at the same time. To illustrate the effect on cost of underutilized pipelines we have calculated the specific cost for different utilisation ratios (see Section 4.3)

As explained in Section 1, costs for transport of CO_2 have been calculated in several ways and this is further detailed in Section 4; Firstly, cost has been calculated separately and been analysed for each of the three part systems; i.e. the collection system, the spines and the distribution system. Secondly, cost has been calculated for complete transport systems with an offshore spine for relevant clusters concentrated around seven of the ten selected sources (Four Swedish and three Finnish hubs). Thirdly, cost has been calculated and compared for *onshore and offshore* “semi-spine” connecting the selected hubs located along the Swedish east coast. The latter has been done since onshore pipelines usually are expected to be less costly than corresponding offshore lines. However, discussions with the oil and gas industry indicate that if the pipeline route goes through large onshore areas with basement rock, cost may very well rise rapidly to ten to twenty times the cost of a corresponding offshore pipe. Also, such a pipeline will probably have to pass numerous water crossings which may affect cost significantly.

Furthermore, costs have been calculated for transport to two alternative storage sites; the Dalders monocline (sandstone aquifer) south-east of Gotland in the Baltic Sea and Utsira south in the North Sea. Calculation of cost for transport to Utsira south has been done since the characterization of the Dalders monocline has not yet advanced to being near what is the case for Utsira, especially with regard to storage capacity and injectivity.

From the above follows that the scenario development assumed in this work builds on the logic of some large sources becoming the first CCS projects in the region, initially using ship transport to a storage location in the Baltic Sea region, the Dalders. Around these initial capture sites, CO_2 export hubs gradually develop as adjacent emitters deploy carbon capture and connect to the hub via onshore collection pipelines. For the long haul transport system this means that shipping capacity is expanded up to the point where eventually, if ever, pipeline costs are lower than shipping, justifying pipeline investment. The distribution system at the storage site in Dalders is scaled up correspondingly, however with a contingency plan to shift to another Baltic Sea site or to storage in the North Sea. In the latter case, shipping would probably be continued. On this basis, this work has explored cluster formations in the Bay of Bothnia, Husum-Vasa, Korsnäs-Meri-Pori and in Oxelösund.

4 Results – cost estimates

4.1 Analyzing the cost of part pipeline systems

As mentioned in Chapter 1, cost was partly calculated separately for feeders, spines and distribution lines and partly for complete systems assuming hubs being developed at the site of each of the “first movers”. This section analyses the results for each of the part systems individually.

4.1.1 Feeders and collection system

Calculating the cost of feeders separately, i.e. the feeders are not connected to a complete transport system, implies that we take no position with regard to if and when capture will be installed at individual sites since this in most cases will be speculative. Thus, we have applied a generic approach calculating the cost for feeders carrying 100 to 1,700 kt (comprises 163 out of the 170 sources in the region with annual emissions exceeding 100 kt) over 50 to 500 km. We also calculated the cost of some larger feeders assuming that two or more sources will share parts of the feeder, or more specifically, we calculated the cost for 2.2, 2.5 and 3.6 Mt transported over 100, 200 and 300 km. Figure 8 exemplifies results from these calculations, giving how the specific cost depends on transportation volume. Specific cost in Euros per ton is showed on the y-axis.

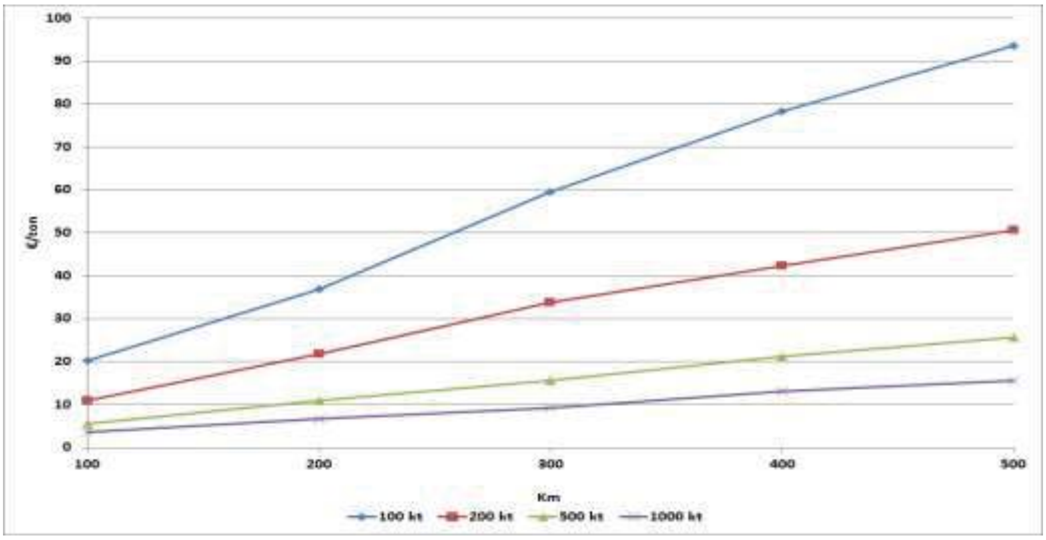

Figure 8 Specific cost for feeders as function of volume and distance

It should be noted that cost is low for the larger feeders over short distances and, the opposite, high for the smaller feeders, e.g. over 100 km the cost ranges from € 3.6/ton for the feeder carrying 1,000 kt to € 20.2/ton for the feeder carrying 100 kt. Obviously sources with low CO_2-volumes up to 200 kt should be located close to the hub to be included in a cluster while on the other hand, large sources capturing 1 Mtpa or more may achieve low cost for connection to a bulk system. In general it can be stated that specific cost declines both as a function of increasing volume and declining distance.

4.1.2 Spines

Next, we calculated the cost of spines, both by ship and by pipeline to two storage sites; Dalders monocline in the Baltic Sea and Utsira in the North Sea, the latter representing an additional transport distance of up to 1,400 km. The cost of spines was calculated both for each of the ten selected sources specifically (see Table 1 and Figure 1) and as a function of increasing transport volume from 1 to 20 Mt per year (see Annex 3). Comparing these costs yields 1) the least costly transport mode for the selected source itself, 2) the volume required for pipeline transport to be the least costly transport mode assuming a hub is developed at the site of the selected source and 3) cost for the least costly transport mode as a function of increasing volume, i.e. in the case of more and more sources being connected to the hub. Cost for subsea templates and control cables have not been included since it can be assumed that both ship and pipeline transport will apply the same injection and storage concept. Table 4 shows specific cost for a spine carrying captured CO_2 from the selected source only, to either Dalders or Utsira.

Table 4: Specific cost for spine to Dalders and Utsira

				Dalders, €/ton			Utsira, €/ton	
Source/Hub	**Location**	**Volume, (tpa)**	**Distance (km)**	**Pipeline**	**Ship**	**Distance (km**	**Pipeline**	**Ship**
Rautaruukki	Raahe	3 374 500	1065	34.2	14.4	2299	77.7	21.1
Neste Oil	Porvo	2 490 500	628	24.7	12.2	1862	79.7	19.5
Fortum	Meri-Pori	2 391 900	644	26.3	12.4	1878	83.6	19.9
Vaskiluoto 2	Vaasa	1 130 500	835	64.7	19.7	2069	165.3	25.4
Fortum	Turku	1 394 000	531	34.2	16.0	1765	118.9	21.8
SSAB	Oxelösund	1 844 500	324	16.6	12.5	1558	84.5	18.1
LUKAB	Luleå	1 691 500	1095	61.5	17.2	2329	137.0	25.9
Cementa	Slite	1 215 500	194	15.0	14.5	1428	106.8	21.8
Korsnäsverken	Gävle	1 130 500	601	47.1	18.3	1835	146.9	24.2
M-real Sweden	Husum	1 436 500	828	53.2	17.3	2062	134.6	22.7

As can be seen from Table 4, the cost for ship transport is considerably below corresponding transport cost by pipeline. The reason for this is the combination of relatively modest volumes and long distances. Also there are relatively modest additions to cost transporting the CO_2 by ship an additional almost 1,400 km to Utsira.

However, as can also be seen, in all cases the costs are considerably higher than what is typically given for transportation cost from large power plants (some 5-10 €/ton). This is of course due to the fact that all emission sources in the Nordic countries are a magnitude smaller than a typical large coal fired power plant (emitting some 10 Mt/yr).

Figure 9 shows all sources in the Nordic region (excluding Iceland) emitting 100 kt CO_2 or more in 2010. The ten selected sources are highlighted in red. The figures next to each of the ten selected sources show the volume required for pipeline transport to become less costly than ship transport and the corresponding transport cost for that specific volume, in both cases to the Dalders monocline. Again, as mentioned above, the cost estimates include only the spine itself, i.e. cost for additional equipment at the storage site such as subsea templates and umbilicals has not been included.

Figure 9 CO_2 emission sources in the Nordic region

In section 4.2 four clusters are analysed; Bay of Bothnia, Husum-Vasa, Korsnäs-Meri-Pori and Oxelösund, respectively.

Combining the information contained in Table 4 and Figure 9 it can be concluded that ship transport gives lower cost in all cases shown for each of the selected sources individually and that the further away from the storage site, the higher the volume required for pipeline transport to give the lowest cost. The latter is even more obvious when another almost 1,400 km is added to the transport distance for storage in Utsira. In this case ship is the least costly transport mode from any of the ten selected sources for any volume up to at least 20 Mtpa. It can also be concluded that the three most northern located hubs in both Finland and Sweden will have a hard time reaching the volumes required for pipeline transport to become less costly than shipping, all the more since a substantial part of the emissions in the region is biogenic. This suggests that combined Finnish-Swedish spines may be advantageous from a cost perspective, at least north of Korsnäs in Gävle and Meri-Pori in Naantali. Another way to achieve sufficient volumes for pipeline transport could be to connect several hubs in Sweden through an on- or offshore pipeline. For instance sources located around Gävle-Oxelösund-Gotland could probably relatively easy reach the required volumes provided storage can take place in Dalders. Both these possibilities are analysed and discussed below.

4.1.3 Distribution lines

As mentioned above, the distribution line(s) connect the spine to the injection site(s) and the distribution system is assumed to be the same for ship and for pipeline for the same volume and assumed injectivity which in this work has been set to 0.5 and 1.0 million tons per well per year. If multiple reservoirs are required to store the transported volume or if more than four injection wells are required then the distribution line is followed by additional 10 km distribution lines, each terminating in a subsea template. An umbilical control cable is assumed to go from the first template to a land-based control station at Gotland’s south coast or, in the case of transport to Utsira, to a nearby platform (assumed to be located 50 km away from the template). Additionally, it has been assumed a 10 km control cable between each template. Starting from the first injection site, distribution lines at Dalders are assumed to go in a north-eastward direction towards the Bay of Riga while at Utsira the distribution lines are assumed to go in a northern direction from the first injection point. Cost for water producers to manage pressure increase within the reservoir has not been included. Figure 10 compares the cost of distribution lines as a function of increasing volume for the two assumed well injectivity rates; 0.5 and 1.0 Mtpa.

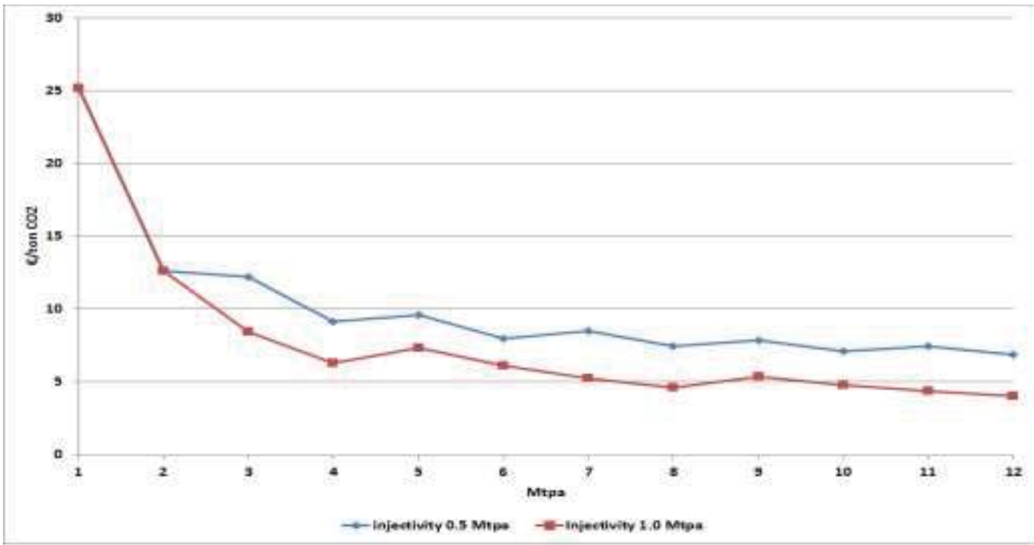

Figure 10 Cost for the distribution system at the storage site as a function of volume and well injectivity

The dominating cost item in the distribution system is the subsea template and the almost 130 km long (in the case of storage in Dalders) main control cable going from template number one to a land based control station on Gotland. Since we have selected a four-slot template with four well heads, a well injectivity of 0.5 and 1.0 Mtpa implies an additional distribution line and template for each 2 and 4 Mtpa additional injection requirement respectively (i.e. a template is installed for well no 1, 3, 5 and so forth for an injectivity of 0. 5 Mtpa and for well no 1, 5, 9 and so forth for an injectivity of 1.0 Mtpa). In both injectivity cases, specific cost goes down as a consequence of increasing volumes. The reason for this is the relatively large capital expenditure for the main control cable amounting to some € 205 million. However, seen from a total system perspective, this would have little effect on overall cost.

4.2 Analysing the cost of cluster systems

There are numerous potential cluster developments both on the Finnish and Swedish side of the Baltic Sea. In this work we have focused on establishing cost for clusters concentrated around the selected sources listed in Table 1 assuming that hubs are being developed at those sites. The clusters have been designed based on 1) that all sources, which are included in a cluster, are connected to its closest hub (unless otherwise stated explicitly) and 2) sufficient number of sources is connected to each hub so that the threshold volume is reached where pipeline transport becomes the least costly transport mode (see Figure 9).

All clusters analysed in this section comprise the same system components as described in Section 1, i.e. feeders, spine and distribution lines. Moreover, each system component is also designed in exactly the same way as described in Section 1 and visualised in Figure 3 with regard to templates, control cables and assumed well injectivity.

4.2.1 Bay of Bothnia Cluster

As indicated above, at least 18 Mt will have to be captured and transported to storage sites annually to make pipeline transport less costly than ship transport from the Bay of Bothnia. Furthermore, 18 Mtpa is under the assumption that the bulk system is utilised to its full capacity already from the beginning – a development that is very unlikely. Smaller volumes than 18 Mtpa should utilise ship transport.

Thus, in order to illustrate large-scale cluster systems from the Bay of Bothnia, capture of CO_2 was assumed to be installed at nine individual sites in Sweden with a combined estimated capture volume of 5.9 Mt per year and at nineteen individual Finnish sites with a combined estimated capture volume of 14.3 Mt per year. This gives a total bulk transport system of 20.2 Mr per year of which 8.7 Mt originates from biogenic sources (2.2 Mt in Sweden and 6.5 Mt in Finland). The selected sources include all sources in the region emitting at least 100 kt CO_2 in 2010 and which are located closer to the selected hubs at Luleå and Raahe than to any other of the selected hubs.

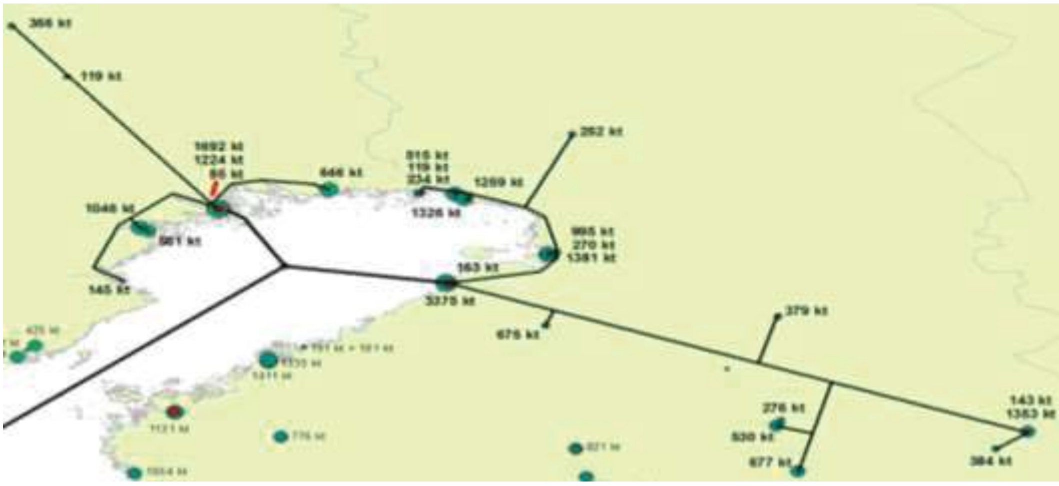

Figure 11 Collection system (feeders) in the Bay of Bothnia cluster

Figure 11 gives an overview of the collection system as well as estimated capture volume at each individual site for the Bothnia Bay CCS cluster system. As mentioned above, the illustrated systems transport

5.9 and 14.3 Mtpa from Swedish and Finnish capture plants respectively.

Each of the two national systems was assumed to end in an offshore PLEM (see Figure 4) before connecting to a third larger bulk pipeline taking the CO_2 southwards in the Baltic Sea. Cost was calculated both for transport and injection into the Dalders structure and into the southern part of Utsira. The number of distribution lines and templates depend on well injectivity and the volume that needs to be injected. In other words, assuming a transport volume of 20.2 Mtpa and an injectivity of 1 Mtpa per well, will require five 4-slot templates and 4x10 km distribution lines assuming that one of the templates can take 4.2 Mtpa (e.g. 1.05 Mtpa per well). Cost was calculated for the Swedish system isolated, for the Finnish system isolated as well for the combined system. Furthermore, cost has also been calculated for the separate parts of the system, i.e. for the collection system (feeders), for the bulk system (the spine) and finally for the distribution system.

Total pipeline length to storage in Dalders assuming an injectivity of 1.0 Mtpa per well was 3,075 km including 1,705 km feeder system of which 655 km in Sweden and 1,050 km in Finland. Total pipeline length for the corresponding Utsira system was 4,310 km.

Specific cost for the entire system was calculated to between € 19.1 and € 22.1 per ton CO_2 for transport to Dalders assuming an injectivity of 1.0 and 0.5 Mtpa per well respectively while corresponding cost for transport to Utsira ranged between € 31.9 and 34.9 per ton respectively.

Table 5: CAPEX and annual OPEX for each system, M€ (Q3, 2012)

-	Sweden		Finland		Total	
Site/Injectivity	CAPEX	OPEX/yr	CAPEX	OPEX/yr	CAPEX	OPEX/yr
Dalders 0.5	1710	59	3943	134	5654	193
Dalders 1.0	1479	51	3382	117	4861	169
Utsira 0.5	2710	89	6375	209	9085	299
Utsira 1.0	2479	82	5813	192	8293	274

Table 5 shows total CAPEX and annual OPEX for the Finnish and Swedish parts of the transport system when applying different assumptions on injectivity. The share of CAPEX and OPEX for respective country for the spine and the distribution system is based on the share of the total flow in each of the two part systems, 29 and 71% for the Swedish and Finnish system respectively. As can be seen, cost increases by around 60% when taking the CO_2 the more than 1,200 km extra distance to storage in Utsira. Also, both CAPEX and OPEX increases by between 14 and 17% when injectivity is reduced from 1.0 to 0.5 Mtpa per well in the case of Dalders and by between 9 and 10% in the case of Utsira. Finland account for roughly 70% of the cost while Sweden account for 30% corresponding to the share of CO_2 in the combined system.

Table 6 shows CAPEX and annual OPEX for the feeder system, for the spine and for the distribution system in Finland and Sweden respectively assuming transport to Dalders and an injectivity of 1.0 Mtpa per well. The spine system includes all pipelines starting from the selected hubs, i.e. at Rautaruukki steel in Raahe and at LUKAB in Luleå, and terminates at the storage site including the first subsea template.

Table 6: CAPEX and annual OPEX for part systems to Dalders, M€ (Q3, 2012)

	Sweden		Finland		Total	
Part System	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**
Feeders	272	10	671	26	943	35
Spine	1022	36	2262	78	3284	114
Distribution	185	6	450	14	634	19
Total System Cost	**1479**	**51**	**3382**	**117**	**4861**	**169**

Note: System cost is based on assumed injectivity of 1.0 Mtpa per well

The spine accounts for almost 70% of CAPEX and annual OPEX for the combined system while the collection system (feeders) account for around 20%. The share in total system cost is roughly the same when looking at cost of part systems in Sweden and Finland.

Including some of the sources in the cluster is costly due to the low transport volume in combination with a long transport distance. This is particularly the case with LKAB's plants in Kiruna and Malmberget which combined are assumed to capture and transport up to 485 kt over 425 km, i.e. some 8.2% of the total Swedish system. However, these two sources alone account for more than 43% of CAPEX for the total collection system (€ 118 million out of € 272 million for the system) and 40% of annual OPEX. Likewise, the 115 km long feeder from Rönnskärsverken transporting 145 kt before connecting to the pipeline from Smurfit Kappa in Piteå account for 12% of CAPEX for the total collection system. Consequently, these sources add much more to the system cost than what they contribute in form of volume. On the other hand and as shown in Table 6, the feeders account for less than 20% of total system cost.

There are many reasons why a bulk CO_2 pipeline from the Bay of Bothnia appears unrealistic; First of all, in order for pipeline transport to become less costly than ship transportation, it will require almost all sources located in the region with annual emissions exceeding 100 kt to install capture, the farthest located as far as 350 km from the hub (other sources in the region are likely to utilise other hubs located closer to the storage site than the Rautaruukki/Luleå sites). Also, most feeder systems in the Bothnia Bay region will probably have to pass numerous water crossings as is clearly illustrated in Figure 12. These are likely to add further to cost beyond the 20% added in our estimates to account for the fact that measurements of distance has been done through a straight line in GIS. In Figure 12 is also indicated the assumed capture volumes at each individual site. In total some 20 Mtpa of CO_2 is collected and piped to hubs in Raahe and Luleå in the system depicted in the figure.

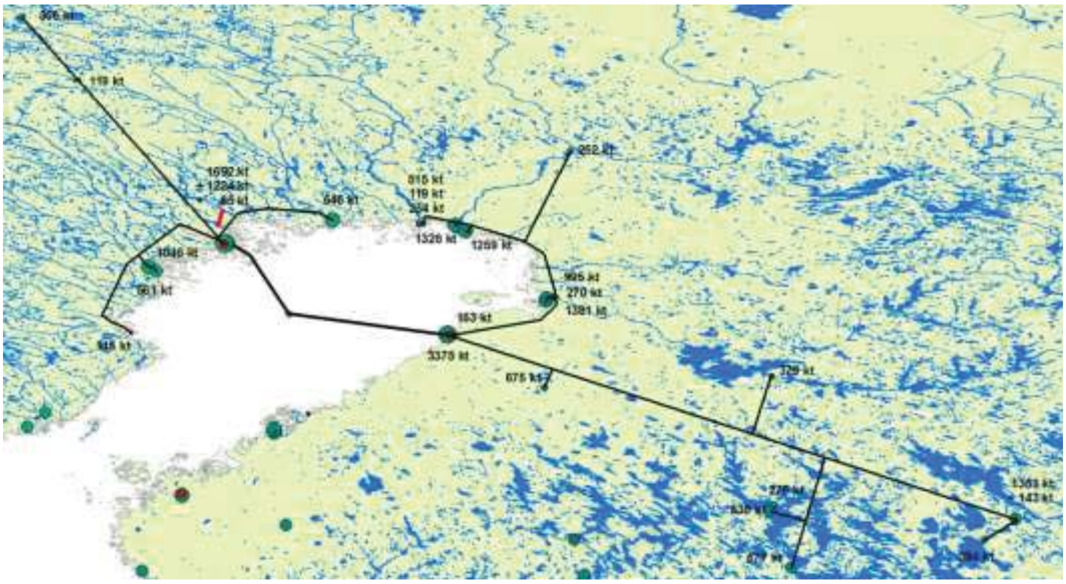

Figure 12 The collection system in the Bay of Bothnia cluster

Illustrating the potential of required water crossings.

4.2.2 Husum-Vasa Cluster

Referring to Figure 9, transport volumes from hubs developed at Husum and Vasa will need to be at least 13 Mtpa for pipeline transport to become less costly than shipping – again assuming all sources connected to the network from day one, a system development that is very unlikely to occur in practice.

The two hubs in the Husum-Vasa system are assumed to be located at the Vaskiluoto 2 power station in Finland and at M-Real's plant in Husum. The transport system comprises nine Swedish sources and fourteen Finnish sources with an estimated capture volume of 4.8 and 8.7 Mtpa respectively of which 4.4 and 3.6 Mt from biogenic sources in Sweden and Finland respectively. The system includes Etelä-Savon

Energia's plant in Mikkeli (the 353 kt plant located farthest to the east in the Finnish system depicted in Figure 13) which has a much shorter distance to the hub located in Porvoo. However, the Mikkeli plant was included to ascertain a total transport volume of more than 13 Mt and the Mikkeli feeder connects to larger sources after a relatively short distance (120 km). It is nevertheless obvious that the Mikkeli plant will achieve lower cost transporting the CO_2 to the hub in Porvoo. Figure 13 shows the total transport system to the Dalders structure. The numbers refer to capture volume at each site, the red dotted line to the 127 km land based control cable to Gotland while the light green circles illustrate location of the four required subsea templates separated by 3x10 km distribution pipelines (the first template and first four injection wells are placed at the end of the spine) and each having 4 well heads.

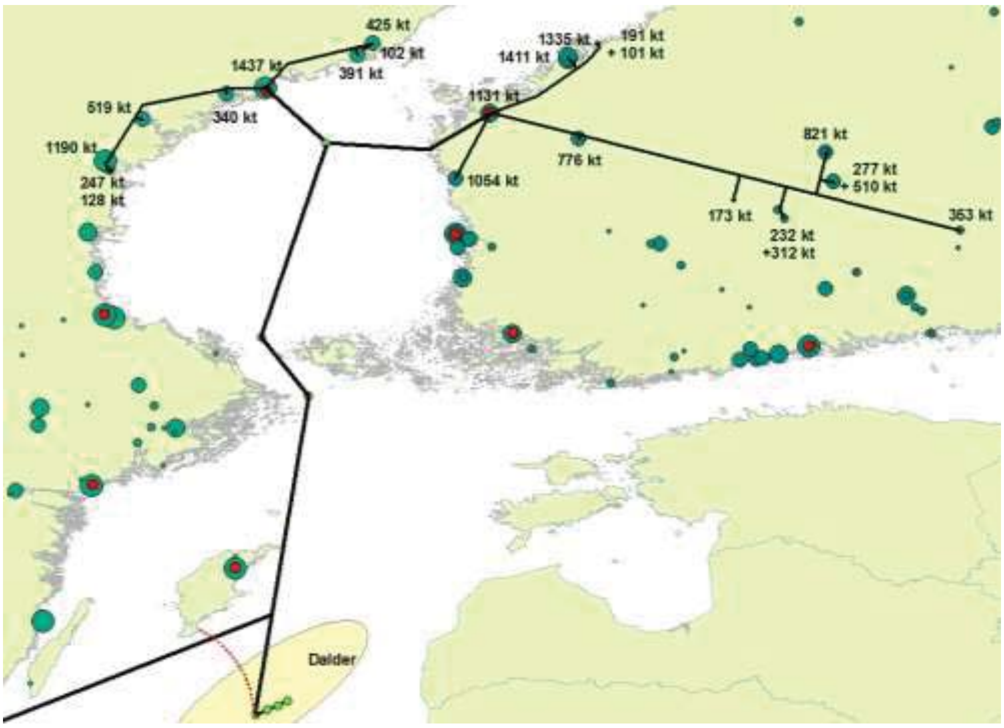

Figure 13 Pipeline transport system for the Husum-Vasa cluster

The numbers refer to estimated capture volume at individual sites. Light green circles refer to subsea templates while the red, dashed line refers to control cable to control station on Gotland.

System specific cost were calculated to range between € 20.1 and 22.7 per ton for transport to Dalders depending on an injection rate of 1.0 and 0.5 Mtpa per well respectively. Corresponding transport cost to Utsira range between € 35.5 and 38.2 per ton respectively. In other words, slightly higher specific cost than for the Bothnia Bay cluster described above. Total pipeline length to storage in Dalders assuming an injectivity of 1.0 Mtpa per well was 2,265 km including 1,165 km feeder system of which 345 km in Sweden and 820 km in Finland. Total pipeline length for the corresponding Utsira system is 3,530 km. Table 7 shows CAPEX and annual OPEX in Finland, in Sweden and in total for the two transport systems to Dalders and Utsira assuming an injectivity of 0.5 and 1.0 Mtpa per well.

Table 7: Husum-Vasa cluster CAPEX and OPEX, M€ (Q3, 2012)

	Sweden		Finland		Total	
Site/Injectivity	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**
Dalders 0.5	1374	46	2496	86	3870	132
Dalders 1.0	1205	41	2189	77	3394	118
Utsira 0.5	2350	77	4271	140	6621	217
Utsira 1.0	2180	72	3963	131	6143	203

Taking the CO_2 to Utsira raises CAPEX by between 71 and 81% and OPEX by between 63 and 76%. Lower injectivity raises CAPEX and annual OPEX by between 12 and 14% in the case of Dalders and by between 7 and 8% in the case of Utsira. Table 8 shows CAPEX and annual OPEX distributed between the various parts of the transport system to Dalders assuming an injectivity of 1.0 Mtpa per well.

Table 8: Husum-Vasa CAPEX and OPEX by system part to Dalders, M€ (Q3, 2012)

	Sweden		Finland		Total	
Part System	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**
Feeders	209	8	472	18	681	25
Spine	830	29	1415	50	2245	79
Distribution	166	5	302	9	468	14
Total System	**1205**	**41**	**2189**	**77**	**3394**	**118**

Note: System cost is based on assumed injectivity of 1.0 Mtpa per well

The feeder system contributes between 17 and 18% to the cost in Sweden and between 22 and 23% to the cost in Finland. The spine contributes between 69 and 70% to the total system cost in Sweden and 65% in Finland. CAPEX and OPEX for the Swedish system account for some 35% of the total system cost corresponding to Sweden's share of total CO_2-volume being transported through the system.

In the Husum-Vaasa cluster most sources may easily fit into the cluster system described above since most of the smaller sources are located close to larger sources. The one exception from this is the Mikkeli plant which, if excluded from the system, will reduce the total volume very close to the level that will be required for pipeline transport to yield lower cost than by ship.

4.2.3 Korsnäs – Meri-Pori Cluster

The two hubs in the system are assumed to be located at Korsnäsverken in Gävle and at Meri-Pori power station in Pori. As shown in Figure 9, at least 10 Mtpa will have to be transported from the hubs in Korsnäs and Meri-Pori in order for pipeline transport to yield lower transport cost than ship. The designed Korsnäs Meri-Pori cluster comprises thirteen plants in Sweden with combined estimated capture volume of 5.4 Mtpa and nine Finnish plants with a combined estimated capture volume of 6.6 Mtpa. CO_2 emitted from biogenic sources account for 50% of the transported CO_2-volume, 4.5 Mt in Sweden and 1.4 Mt in Finland. The collection system is depicted in Figure 14 along with estimated annual capture volume at each site that has been included in the system.

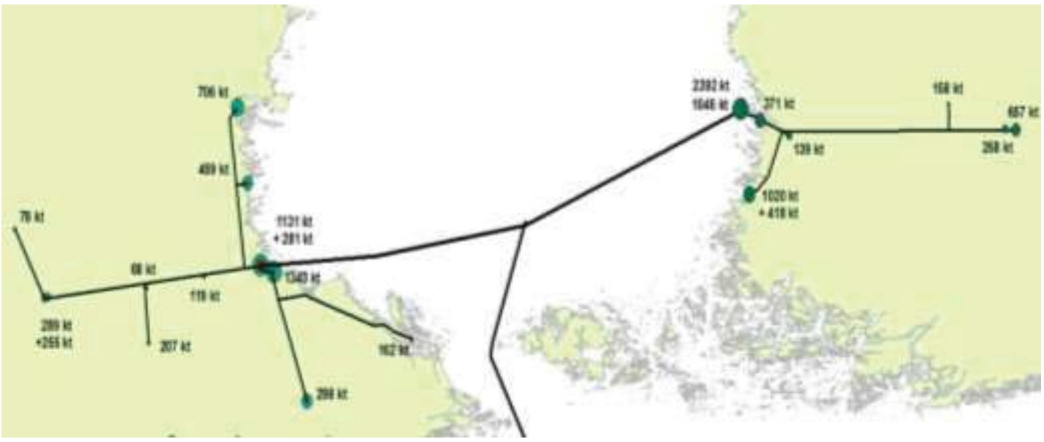

Figure 14 Collection system for the Korsnäs Meri-Pori cluster

The numbers refer to the estimated capture volume at each individual site.

The total system to Dalders assuming an injectivity of 1.0 Mtpa per well comprises 1,734 km of pipeline of which 585 km of feeders in Sweden and 245 km of feeders in Finland. The total pipeline distance to Utsira is 3,155 km, again assuming an injectivity of 1.0 Mtpa per well.

Specific cost for the total system is calculated to range between € 17.3 and 20.2 per ton CO_2 depending on injectivity of 1.0 and 0.5 Mtpa respectively. Taking the CO_2 to Utsira would raise specific cost to between € 36.6 and 39.5 per ton for an injectivity of 1.0 and 0.5 Mtpa respectively.

Table 9 shows total CAPEX and annual OPEX in Sweden, Finland and for the total system for each of the four transport systems to Dalders and Utsira.

Table 9: Korsnäs Meri-Pori cluster CAPEX and OPEX per system, M€ (Q3, 2012)

	Sweden		Finland		Total	
Site/Injectivity	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**
Dalders 0.5	1487	51	1577	55	**3064**	**107**
Dalders 1.0	1273	45	1313	47	**2586**	**92**
Utsira 0.5	2899	92	3313	106	**6212**	**198**
Utsira 1.0	2689	86	3053	98	**5742**	**183**

While the Swedish CO_2-volume accounts for 45% of the total CO_2 volume in the system, the Swedish system accounts for 49% of total cost in the case where the CO_2 is transported to Dalders and 47% in the case where the CO_2 is transported to Utsira. The reason for this is the more costly feeder system in Sweden as can be seen in Table 10 which shows cost of the various part systems in the case of 1.0 Mtpa well injectivity in Dalders.

Table 10: Korsnäs Meri-Pori cluster CAPEX and annual OPEX for part systems to Dalders, M€ (Q3, 2012)

	Sweden		Finland		Total	
Part System	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**	**CAPEX**	**OPEX/yr**
Feeders	303	10	188	7	490	17
Spine	830	31	953	36	1782	66
Distribution	141	4	173	5	314	9
Total System	**1273**	**45**	**1313**	**47**	**2586**	**92**

Note: System cost is based on assumed injectivity of 1.0 Mtpa per well

As can be seen from Table 10, the Swedish feeders account for 24% of total CAPEX for the Swedish system while the Finnish feeders only account for 14% of corresponding Finnish CAPEX. The reason for this is the combination of long transport distances and low volumes in the Swedish collection system compared to the Finnish collection system. The total pipeline length of the Swedish system is 584 km while corresponding length for the Finnish system is 244 km while transported CO_2-volume is 5.4 and 6.6 Mtpa respectively.

There are in particular two feeders that could be excluded in the Swedish system, namely the feeder from SMA in Rättvik carrying 78 kt CO_2 over 60 km before linking to a pipeline from Stora Enso in Kvarnsveden and the feeder system from Hallsta Paper mill and Boländeranläggningarna carrying 162 kt and 298 kt over 88 and 85 km respectively before connecting to each other 25 km south of Stora Enso's plant in Skutskär. Combined, these feeders account for 24% of feeders CAPEX but only 10% of the CO_2-flow in the Swedish system.

4.2.4 Oxelösund cluster

The cluster in Oxelösund comprises only Swedish sources since it does not need to include Finnish sources to reach the defined threshold volume where pipeline transport becomes less costly than ship transport. Two systems have been designed; the “small Oxelösund cluster” comprising seven sources and transporting 4.2 Mtpa (of which 1.9 Mtpa biogenic) directly to the storage site and the “large Oxelösund cluster” comprising thirty-two sources and transporting the CO_2 via Cementa’s Slite plant on Gotland to the storage site. The large cluster transports 13.6 Mtpa including Cementa’s plant on Slite and of which 7.8 Mtpa is biogenic CO_2. The hub is in both cases located on SSAB’s plant in Oxelösund. Figure 15 shows the two systems with the smaller system illustrated by a dotted line while the larger system includes all lines on the Swedish mainland plus the pipeline via Gotland to Dalders, i.e. the larger system includes the smaller system (apart from the offshore spine from SSAB Oxelösund directly to Dalders). Again, the numbers refer to the estimated annual capture volume from each individual site.

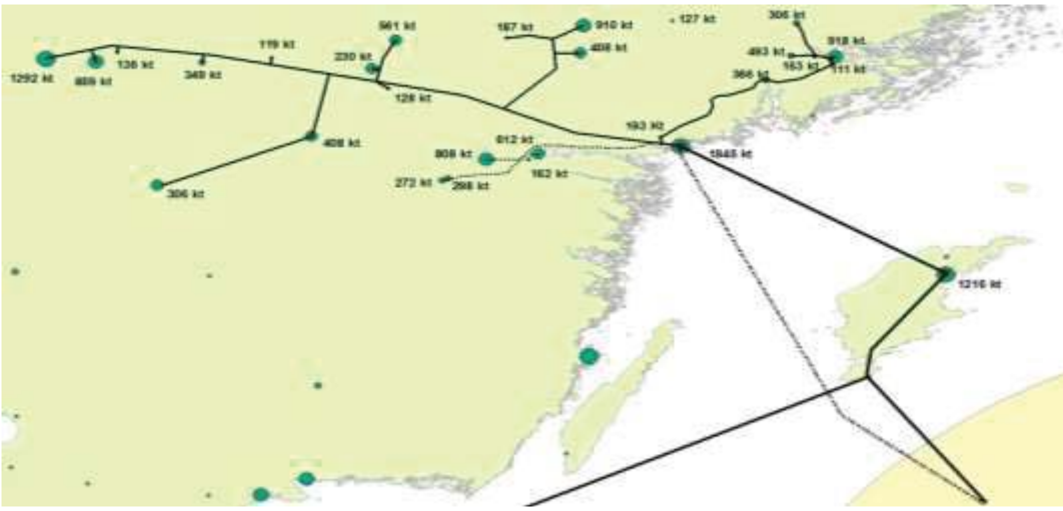

Figure 15 Transport systems for the Oxelösund clusters

The small cluster (dashed line) and the large (whole line plus the onshore part of the dashed line).

As can be seen in Figure 15, some of the anticipated capture sites are located far to the west, in fact closer to Lysekil on the Swedish west coast than to the assumed hub at SSAB in Oxelösund. For these sources it will of course be far less costly to go via Lysekil on the west coast if storage takes place in Utsira. Nevertheless, they have been included for the case of storage in the Dalders structure in the Baltic Sea. Also, Kalkproduktion Storugn’s facility on Gotland could easily be included in the large Oxelösund scheme having a marginal effect on total cost since this would only add the cost of an eighteen km long pipeline carrying some 145 kt CO_2 before connecting to the spine in Slite[4].

The smaller Oxelösund cluster has a total pipeline length ranging from around 520 km (of which 160 km feeders) when storage takes place in Dalders, to around 1,685 km when storage takes place in Utsira (see Footnote 2). Table 11 shows CAPEX and annual OPEX for pipeline and pump respectively as well as specific cost as a function of storage site and assumed injectivity.

Table 11: **Small Oxelösund cluster CAPEX, OPEX and specific cost**

	Pipeline		Pump		
	Total CAPEX	OPEX/yr	Total CAPEX	OPEX/yr	Specific Cost
Storage/Inject	M€	M€	M€	M€	€/ton
Dalders 0.5	1019	31	30	3.6	19
Dalders 1.0	865	26	30	3.5	17
Utsira 0.5	2548	76	30	4.2	47
Utsira 1.0	2395	72	30	4.1	44

As can be seen from Table 11 and as expected, it is mainly pipeline cost that increases when the CO_2 has to be transported to Utsira. The number of pumps in the system stays the same independent on storage site although the pressure is raised considerably increasing annual OPEX by 17%. Specific cost rises by more than 16% when injectivity in Dalders is reduced from 1.0 to 0.5 Mtpa per well.

The large Oxelösund cluster has a total pipeline length ranging from around 1,455 km, of which 1,030 km feeders when storage takes place in Dalders, to around 2,720 km when storage takes place in Utsira. As mentioned above, for some of the sources included in the large system, pipeline transport to the hub at Oxelösund is only less costly than ship when the CO_2 is stored in the Baltic Sea. Table 12 shows pipeline and pump CAPEX plus annual OPEX and specific cost as a function of storage site and injectivity.

[4] CAPEX for the feeder from Kalkugn's facility was calculated to € 8.4 million while annual OPEX was calculated to € 0.3 million and specific cost to € 4.3/ton CO_2.

Table 12: **Large Oxelösund cluster CAPEX, OPEX and specific cost**

	Pipeline		Pump		
	Total CAPEX	**OPEX/yr**	**Total CAPEX**	**OPEX/yr**	**Specific Cost**
Storage/Inject	**M€**	**M€**	**M€**	**M€**	**€/ton**
Dalders 0.5	2457.1	73.7	134.4	16.4	15.1
Dalders 1.0	1986.1	59.6	134.4	15.8	12.5
Utsira 0.5	4833.9	145.0	134.4	23.0	28.6
Utsira 1.0	4362.9	130.9	134.4	22.4	26.0

Comparing Tables 11 and 12, it can be observed (as expected) that specific cost is significantly lower for the large cluster than for the small cluster, in fact specific cost is reduced by nearly 25% for the larger cluster when assuming an injectivity of 1.0 Mtpa per well and storage in the Dalders structure. When storage takes place in Utsira, the larger system has around 40% lower specific cost than the smaller system although storage in Utsira is, as mentioned above, likely to lead to a different configuration of the feeder system and smaller volumes since some of the sources are likely to choose another route via the Swedish west coast instead of the east coast.

In the large Oxelösund cluster the cost of the collection system account for one third of cost (both CAPEX and annual OPEX). This is of course due to a comprehensive onshore network in combination with a relatively short spine compared to the spine in the other clusters in Sections 5.1-5.3. Table 13 shows CAPEX and annual OPEX per part system assuming an injectivity of 1.0 Mtpa per well.

Table 13: CAPEX and OPEX per part system large Oxelösund cluster

	CAPEX, M€	**OPEX/yr, M€**
Feeders	718	26
Spine	934	36
Distribution	469	14
Total	**2121**	**75**

Note: System cost is based on assumed injectivity of 1.0 Mtpa per well

In the Oxelösund clusters there are no feeders that appear particularly costly, i.e. the collection systems could, from a cost perspective, be designed as illustrated in Figure 14. In order to avoid lakes and rivers, the small Oxelösund cluster has been routed along the lakes of Roxen and Glan while the large Oxelösund cluster has been routed along the north end of Vänern and passes Vättern on its west side. However, the systems will still have to cross a number of waterways which probably will increase the cost presented in this report as well as complicate and prolong the construction time.

4.2.5 Comparing Swedish on- and offshore semi-spine

Fossil and biogenic sources are located relatively close to each other both on the Finnish and Swedish side of the Baltic Sea. An entirely Swedish system may be routed southwards from Luleå towards Oxelösund and on its way connect to each of the five selected hubs on the Swedish east coast raising the transported volume and thus also reducing the cost. Such a pipeline system could be located either onshore or offshore. An offshore pipeline system is generally assumed to cost more than a corresponding onshore pipeline system. This is also the case with pipeline systems calculated by the cost model applied by Chalmers. It is therefore also interesting to analyse cost for onshore transport solutions. Thus, we have calculated the cost for an onshore spine starting from Lukab in Luleå transporting CO_2 via the assumed hubs in Husum, Korsnäs and Oxelösund before moving offshore via Cementa’s plant on Gotland to the storage site.

It has been assumed that each hub supplies the estimated capture volume applied in Sections 4.1 to 4.4, i.e. 5.9 Mtpa from the hub in Luleå, 4.8 Mtpa from the hub in Husum, 5.4 Mtpa from the hub in Korsnäs and 12.4 Mtpa from the hub in Oxelösund giving a combined 28.5 Mtpa being transported towards Cementa’s facility on Gotland from which another 1.2 Mtpa is added giving a total volume of 29.7 Mtpa.

The cost calculations include a short connection line from each hub to the main trunk line going southwards from Luleå and cost for the complete distribution system consisting of eight 4-slot subsea templates, each fitted for 4 injection wells with an injection capacity of 1 Mtpa per well, 70 km of distribution lines and corresponding control cables (70 km between each template plus the 127 km and 50 km long control cable to Gotland and platform at Utsira respectively). Thus, assuming that the collection systems for the two semi-spines will be relatively equal[5] to the collection systems designed in Sections 4.1 to 4.4, cost for the on- and offshore semi-spine can be compared to the cost calculations for the four clusters in Sections 4.1 to 4.4. Cost has been calculated for transport to both Dalders and Utsira.

Figure 16 shows the complete on- and offshore semi-spine systems including the CO_2-volumes passing through the various segments of the two pipeline systems. The onshore system is illustrated by a whole line while the offshore system is illustrated by a dotted line. As can be seen, the onshore pipeline will have to pass numerous water crossings

[5] It can be assumed that volumes and distances are equal while diameter and pressure for various segments of the collection systems probably will be slightly different in the two cases since this to some extent will depend on the length of the spine.

which most likely will add significantly to cost. In order to account for this effect system cost has been calculated with three different so-called terrain factors (TF)[6]; 1.0 which is the factor usually applied and which has been applied in all the cases calculated above and additionally, for this case, 1.5 and 2.0.

The TF comes in addition to the so-called "GIS" factor mentioned above adding 20% to onshore distances and 10% to offshore distances measured in GIS (see Section 2.1). However, as mentioned above it should be stressed that discussions with the industry indicate that onshore pipeline cost may rise significantly, widely exceeding the cost of corresponding offshore pipelines if the pipeline has to pass areas with solid basement rock. Also, it should be underlined that such a large scale onshore pipeline risks facing significant local opposition along the route delaying the time schedule, adding further to cost or perhaps making it impossible to get acceptance for such a solution.

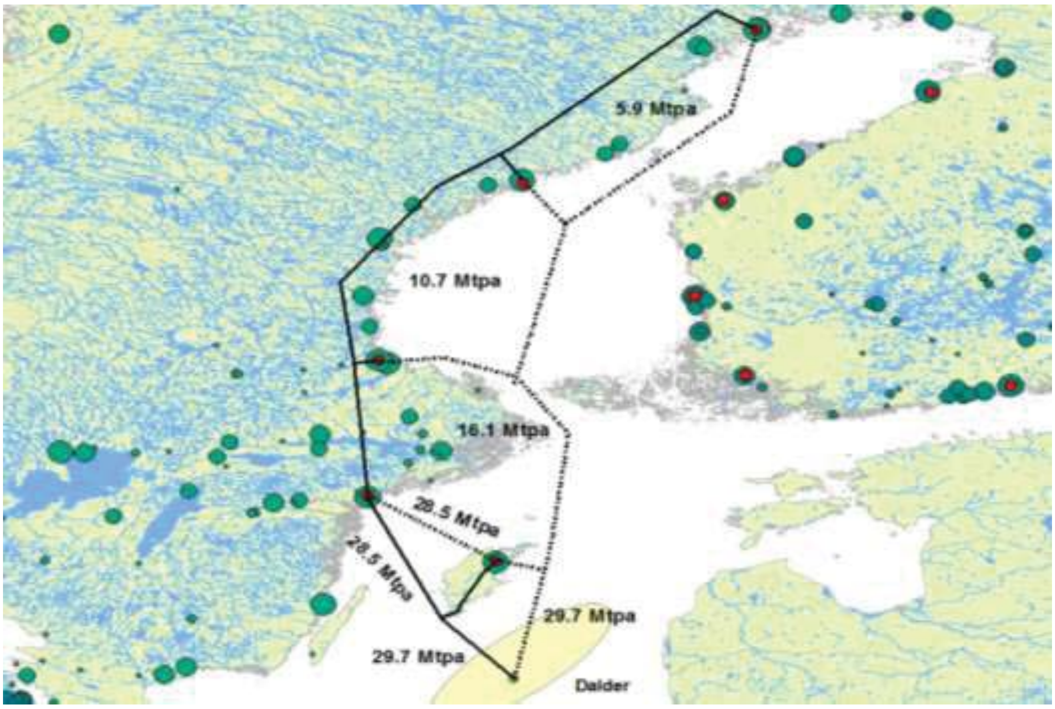

Figure 16 On- and offshore semi-spine

Collecting CO_2 from the selected hubs (see Sections 4.2.1 to 4.2.4). The numbers indicate the annual plateau flow through the various segments of the pipeline.

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6 Typical terrain factors applied by IEA (2002, 2005) is 1.00 for grassland, 1.05 for wooded areas, 1.10 for cultivated land, jungle and stony desert, 1.30 for areas which are less than 20% mountainous and 1.50 for areas that are more than 50% mountainous.

Total pipeline length of the onshore system depicted in Figure 16 with storage in Dalders comes to 1,720 km including 435 km offshore pipelines while the corresponding offshore system has a total pipeline length of 1,800 km. The results from the cost calculations are showed in Table 14.

Table 14: Cost Swedish on- and offshore semi-spine to Dalders and Utsira

	Dalders			Utsira		
System	CAPEX, M€	OPEX, M€/yr	Spec Cost, €/ton	CAPEX, M€	OPEX, M€/yr	Spec Cost, €/ton
Onshore TF 1.0	3690	139	10.24	6957	254	19.03
Onshore TF 1.5	4272	166	12.00	7539	281	20.79
Onshore TF 2.0	4887	193	13.86	8157	308	22.64
Offshore	4756	173	12.98	8148	292	22.09

Length of control cable: 127 km case Dalders and 50 km case Utsira

Specific cost ranges from € 10.2 per ton to € 13.0 in the case of Dalders and between € 19.0 and 22.1 per ton in the case of Utsira. As can be seen from Table 14, cost of the offshore option is slightly below the cost of the corresponding onshore option when a TF of 2.0 is applied. Due to the causes mentioned above however, it is questionable whether a TF of 2.0 is sufficient. Additionally, it will probably be considerably easier and considerably less time consuming to go for the offshore option.

To calculate the cost for a complete system with semi-spines, the cost for collection systems should be added to the cost in Table 14. Sections 4.1 to 4.4 specify the cost for the collection system for each of the hubs delivering CO_2 to the semi-spine in Figure 16. As mentioned above, it may be assumed that the collection systems calculated in sections 4.1 to 4.4 may be relatively identical to the collection systems required for the semi-spines. Therefore, adding the cost for the Swedish collection systems calculated in Tables 6 (Bothnia Bay cluster), 8 (Husum-Vasa cluster), 10 (Korsnäs-Meri-Pori cluster) and 13 (Large Oxelösund cluster) to the cost of the semi-spines in Table 14, would provide a reasonable estimate of total system cost for the semi-spines which then in turn may be compared to total combined cost for the four separate systems. Thus Table 15 shows the cost of the feeder system as well as the cost of the complete system for each of the four clusters calculated in Sections 4.1 to 4.4. Costs are taken from Tables 6, 8, 10 and 13 in Sections 4.1-4.4.

Table 15: Cost of collection and total systems for clusters in Section 4.1-4.4

	Collection System		Complete System	
Cluster	**CAPEX, M€**	**OPEX, M€/yr**	**CAPEX, M€**	**OPEX, M€/yr**
Bothnia Bay	272	10	1479	51
Husum-Vasa	209	8	1205	41
Korsnäs-Meri-Pori	303	10	1273	45
Oxelösund Large	718	26	2121	75
Total	**1502**	**54**	**6078**	**212**

Adding € 1.5 billion to CAPEX and € 54 million to annual OPEX for the semi-spines in Table 14 yields estimated total system CAPEX ranging from € 5,190 million to € 6,387 million for the onshore semi-spine depending on TF and € 6,256 million for the offshore semi-spine. Likewise, estimated annual OPEX ranges from € 193 million to € 247 million for the onshore semi-spine and € 227 million for the offshore semi-spine. In other words, this exercise indicates that an onshore semi-spine comprising Swedish sources only may be a less costly solution than a shared offshore system with Finland if the applied TF of 1.5 is sufficient. On the other hand it can also be stated that an offshore semi-spine comprising Swedish sources only, is fairly competitive against a combined Finnish-Swedish system comprising four separate spines.

Considering the potential for cost increases as well as other potential problems related to large-scale onshore pipelines, an offshore pipeline system appears less costly and realistic whether this would be a combined Finnish-Swedish system or a stand-alone Swedish system.

4.2.6 Cluster systems in summary

Tables 16 and 17 summarize the transport systems calculated in Sections 4.1 to 4.4 to Dalders and Utsira respectively assuming a well injectivity of 1.0 Mtpa. As can be seen, the relative cost range from 12.5 €/ton (Oxelösund large cluster to Dalders) to 36.6 €/ton (Korsnäs-Meri-Pori cluster to Utsira).

Table 16: Compilation Cluster systems to Dalders

	No of	Pipeline	CO_2 volume	CAPEX	OPEX	Specific cost
Cluster	**sources**	**km**	**Mtpa (bio)**	**M€**	**M€/yr**	**€/ton**
Bothnia Bay	28	3 075	20.2 (8.7)	4 861	169	19.11
Husum-Vasa	23	2 265	13.5 (8.0)	3 394	118	20.07
Korsnäs-Meri-Pori	22	1 734	12.0 (5.9)	2 586	92	17.28
Oxelösund large	32	1 457	13.6 (7.8)	2 120	75	12.48
All systems	**105**	**8 531**	**59.3 (30.4)**	**12 961**	**454**	

Table 17: Compilation Cluster systems to Utsira

Cluster	No of sources	Pipeline km	CO_2 volume Mtpa (Bio)	CAPEX M€	OPEX M€/yr	Specific cost €/ton
Bothnia Bay	28	4 310	20.2 (8.7)	8 293	274	31.93
Husum-Vasa	23	3 532	13.5 (8.0)	6 143	203	35.51
Korsnäs-Meri-Pori	22	3 153	12.0 (5.9)	5 742	183	36.56
Oxelösund large	32	2 718	13.6 (7.8)	4 497	153	25.97
All systems	**105**	**13 713**	**59.3 (30.4)**	**24 675**	**813**	

Three of the cluster systems in Tables 16 and 17 are shared between Finland and Sweden, which was simply a requirement to achieve sufficient volumes so that pipeline transport could become less costly than corresponding ship transport. Exactly half the transported volume originates in Sweden including all the CO_2 from Oxelösund.

More than half the transported volume of 59 Mt originates from biogenic sources (30Mt). This may be both positive and negative. If biomass based CCS can be accounted for as "negative emissions" in national GHG inventories to UNFCCC and therefore as a consequence probably also be properly incentivized, then bio CCS, or BECCS, is a big positive. If this does not happen then BECCS will not materialize.

As indicated above, one cluster stands out and that is the Oxelösund cluster to Dalders, where a combination of large volumes and short transport distances make pipeline transport yield a cost around 12.5 €/ton. Also, as shown in Figure 9, only 4 Mt CO_2 is required annually to make pipeline transport yield lower cost than shipping, well below the transport volume applied in the systems calculated in Section 4.2.4 and shown in Tables 16 and 17.

Having to transport the CO_2 all the way to Utsira in the North Sea increases specific cost by between 67% (Bothnia Bay cluster) and 112% (Oxelösund cluster) compared to transport to Dalders. Total CAPEX for all four systems almost doubles, from € 13 billion to € 25 billion while annual OPEX increases from € 454 million to € 813 million. It has been calculated that pipeline transport to Utsira is more costly than ship transport from any of the selected hubs for volumes up to and including at least 20 Mtpa (see Annex).

4.3 The effect of ramp up on cost

As mentioned above, all cluster systems are assumed to transport the plateau volume from day one which is highly unlikely. A more likely development is instead that the various feeders and the distribution systems are developed over a period of time, i.e. new feeders are added and the distribution system is expanded over time as the CO_2-volume expands. However, increasing the volumes through a large bulk pipeline or spine is more difficult, in particular for sources located around the Baltic Sea with long transport distances and with numerous potential sources that may be added to the system over time. This would in turn require either several smaller spines or that the pipeline owner takes the risk of letting the spine operate underutilized for a period of time. Thus, it is interesting to analyse the effect on cost from an underutilized spine.

Figure 17 shows specific cost of the four offshore spines from Bothnia Bay, Husum-Vaasa, Korsnäs and Oxelösund, as a function of increasing utilization ratio until full capacity is reached after ten years. The length of the spines ranges from 1,144 km in the case of Bothnia Bay to 359 km in the case of Oxelösund. Each spine is assumed to terminate in a four-slot subsea template with four well heads and with a 127 km control cable to Gotland. Notice that the y-axis starts on six € per ton CO_2.

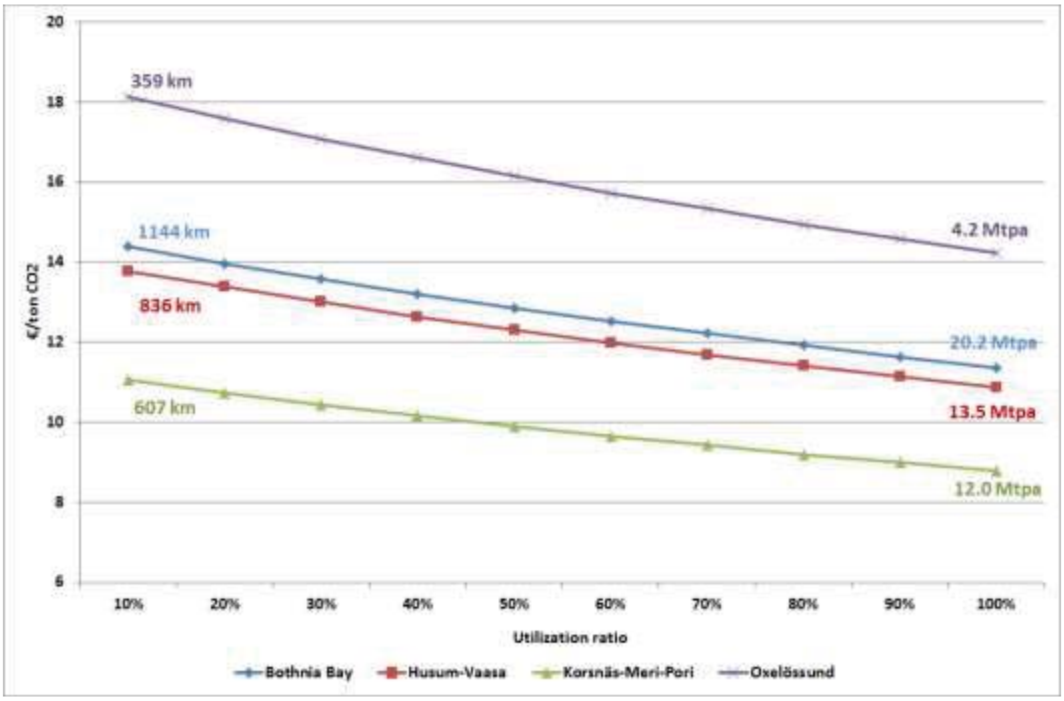

Figure 17 Specific cost of offshore spines from clusters

Bothnia Bay, Husum-Vaasa, Korsnäs and Oxelösund as a function of increasing utilization ratio. In all cases it has been assumed that full capacity (listed to the right in the Figure) is reached after ten years. The pipeline distance is plotted to the left.

Specific cost increases by 26-27% if the spine is utilized only to ten per cent of its full capacity over the first ten years before reaching full capacity in year eleven while the corresponding cost increase is around 13% if the spine is utilized to fifty per cent of its full capacity. The effect increases of course if the spine is underutilized for a longer time period.

The effect on cost from underutilization of pipeline capacity is likely to prevent private investors from building oversized pipelines. All the more so since it is unlikely that an investor will know when (or if at all) full capacity will be reached. This may in turn imply a development of multiple single source–sink systems raising cost and probably also increase the impact on the environment. One possible solution for a bulk pipeline transport system could be if some governmental instrument guarantees the risk taking, or that national government shares the risk with investors through a Public Private Partnership (PPP).

However, as shown in the previous sections, ship transport clearly yields the lowest transport cost not only for most Swedish sources individually but also for most of the potential cluster configurations apart from possibly a cluster concentrated around Oxelösund provided sufficient storage and injection capacity can be found in the Baltic Sea. If Sweden cannot utilize reservoirs in the Baltic Sea Sweden will have to transport the CO_2 to reservoirs in the Skagerrak area or in the North Sea[7] which will require even larger volumes for pipeline transport to be the most cost effective transport mode[8].

[7] Onshore pipelines across Sweden and Norway via Värnes to reservoirs in the Norwegian Sea or northwards from Bay of Bothnia via Hammerfest/Melkøya to reservoirs in the Barents Sea are likely to face numerous problems related to water crossings, height differences and local opposition which is likely to significantly increase the cost. It is therefore questionable whether this is a feasible transport option.

[8] Sources located along the Swedish west coast plus some of the sources included in the Oxelösund cluster (Gruvön and Skoghall paper mills, see Section 4.1.4) may easily reach volumes where pipeline becomes cost efficient from for instance Lysekil to Skagerrak or aquifers located along the Danish northwest coast.

5 Benchmark cost estimates

In order to be able to assess the general validity of the cost estimates in this report and thereby also of conclusions drawn, the results of this work are compared to main works given in literature.

5.1 Zero emission platform (2011)

The European Technology Platform for Zero Emission Fossil Fuel Power Plants (known as the Zero Emissions Platform, or ZEP) represents a coalition of stakeholders united in their support for CO_2 Capture and Storage (CCS) as a critical solution for combating climate change. Members include European utilities, oil and gas companies, equipment suppliers, national geological surveys, academic institutions and environmental NGOs. ZEP is an advisor to the EU on the research, demonstration and deployment of CCS. Members of its Taskforce Technology undertook from 2009 to 2011 a study into the costs of complete CCS value chains – i.e. the capture, transport and storage of CO_2 – estimated for new-build coal- and natural gas-fired power plants, located at a generic site in Northern Europe from the early 2020s. Utilising new, in-house data provided by ZEP member organisations, ZEP established a reference point for the costs of CCS, based on a “snapshot” in time (all investment costs were referenced to the second quarter of 2009). Three Working Groups were tasked with analysing the costs related to CO_2 capture, transport and storage, respectively. The resulting integrated CCS physical supply chains, based on these three individual reports, were presented in a summary report.

The ZEP Transport Cost Report used the approach to describe three methods of transport and for each of these present detailed cost elements and key cost drivers. The three methods were 1) Onshore pipeline, 2) Offshore pipeline and 3) Ship transport, including utilities. Interface conditions such as pressure, temperature and flow rates were jointly defined with the respective Working Groups for Capture and Storage Costs and much effort was invested in detailing the assumptions made for each of the transport methods. The CAPEX and OPEX of each mode of transport were estimated using internally available information from participating organisations and industries.

In the ZEP Transport Cost Report, the aim was to deliver cost estimates within an uncertainty range within +/- 30%. The calculations were built on the three similar building blocks as have been used in this Bastor report, i e feeder pipelines, spines (ships and pipelines) and distribution pipelines. As part of the generic ZEP approach, standard source volumes of 2.5, 10 and 20 million tonnes per annum (Mtpa) were applied. These volumes were essentially to represent European continental, standard coal and/or gas fired power plants, which of course marks a significant difference to the chiefly industrial sources of much smaller CO_2 volumes included in the work presented in this report. Furthermore, four typical spine transport distances were used, 180, 500, 750 and 1 500 km's. These are generally shorter distances than the real numbers used in our calculation. A third difference is that the ZEP report used also onshore storage as an alternative, for which obviously only pipelines were analysed.

As to the estimated costs, the results of this work come out higher, due to lower volumes from a higher number of small sources and at greater distances, both for feeders and for spines. Costs for feeders (collections systems) have also been estimated in more detail and with higher specific costs as a result. There is, however, reasonable consistency which is shown by the example Nestle Oil at Porvo (cf Table 4). With an annual volume of 2.5 Mtpa and a distance to Dalders of 690 km's, the specific transport costs of this work are 24.7 and 12.2 €/ton for the pipeline and ship spines, respectively versus the corresponding ZEP numbers being 29 and 17 €/ton, the general assumptions being fairly equal. It should be noted that neither this work nor the ZEP work includes costs for compressing the CO_2 up to 110 bar.

The ZEP report concludes that large volume systems will deliver the lowest specific costs but that they require long range central planning already in the technology demonstration phase in order to reach maximum capacity utilization. This agrees with the results commented in Chapter 4. See also Annex 3, which shows specific shipping costs decreasing by 47% for increasing volumes from 1 to 10 Mtpa and with 85% for pipelines for the same volume variation. This supports the conclusion that building up transport volume through clustering point sources around export points (hubs) will contribute to keeping costs lower than would otherwise be the case for isolated projects, carrying the entire transport system cost.

5.2 CO_2 Europipe (2010)

The CO_2 Europipe project was an EU-funded project under the seventh framework programme running from April 2009 to late 2011. The project aim was to present a roadmap towards a Europe-wide infrastructure for transport and storage of CO_2.

The Europipe project focuses on pipeline transport and source-sink matching and includes three different scenarios for build-up of CCS volumes; a reference scenario, an offshore only scenario with no onshore storage and an EOR (Enhanced Oil Recovery) scenario. The network and the CO_2-flow within Sweden is basically the same in all three scenarios starting to build up a CO_2 transport network by 2030.

Figure 18 has been taken from CO_2 Europipe (2010) and shows the F Swedish transport system (as well as the corresponding Finnish system) in 2050 with associated CO_2-flow (in Mtpa) through the various segments of the pipelines (black arrows). Blue circles illustrate clusters of sources while green and blue polygons illustrate clusters of gas fields and aquifers respectively used for storage.

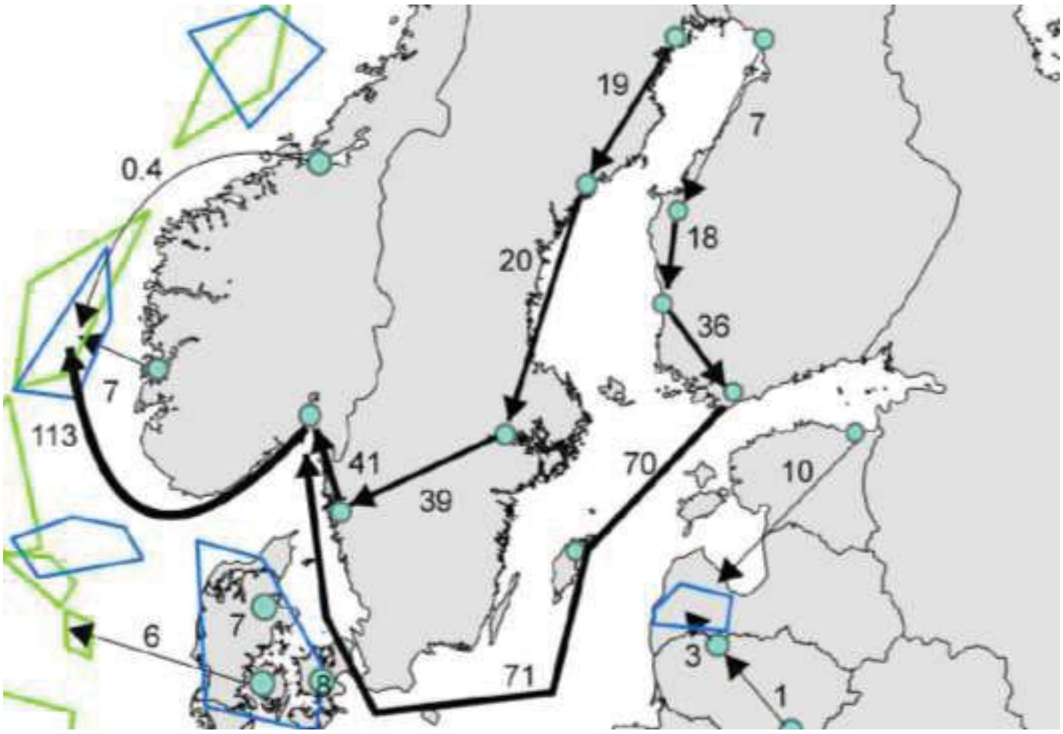

Figure 18 Proposed CO_2 pipeline Sweden and Finland 2050

The numbers indicate the transportation flows in Mtpa.
(Europipe, 2010)

As can be seen from Figure 18, some 19 Mtpa is assumed to be captured and transported from the Luleå region in 2050 which is considerably above current (2010) emissions (since the Finnish emissions are not included but transported in a separate Finnish pipeline system). In fact, it is more than three times the estimated capture volume of 5.9 Mtpa in Section 5.1. There is no information in the report detailing which sources are included in the Luleå cluster but as can be seen from Figure 18, it does not appear to include sources on the Finnish side of the Bothnia Bay and even if it did, the anticipated capture volume transported from Luleå is still much above current emissions. According to the CO_2-Europipe report, emissions and capture potential in

2030 are based on projections taking the basis in a report prepared by the European Commission in 2007 (EC 2007) which provides emission trajectories to 2030 under different policy assumptions. Emissions and capture potential in 2050 were thereafter obtained by extrapolation, taking into account the assumptions of a so-called policy scenario for which however few details are revealed with regard to industrial emissions.

Figure 18 does not include any information on the potential storage sites in the Baltic Sea. In fact, the report states explicitly that Finland and Sweden lack national storage capacity. Thus all CO_2 from Finland and Sweden is transported to the North Sea.

The Europipe project clearly focuses on pipeline transport as mentioned above but states that ship transport may be valuable either during build-up of CO_2-volumes or in cases where ship transport clearly is the least costly transport solution which basically applies to smaller sources/clusters over relatively long transport distances. Also, according to Europipe, shipping offers more flexibility both on the supply and storage side, it can adequately cope with fluctuating transport volumes and ship transport may also mitigate network downtime risks (complementing pipeline systems) and easily switch between multiple storage sites, for instance through utilization of several smaller reservoirs.

The Europipe project provides some basic cost data for pipelines and ships (CO_2 Europipe 2011). For an onshore pipeline larger than 16 inches they quote capital cost (investment) of € 50 per meter and inch which translates into € 1 million for a 20 inch pipeline per kilometre while corresponding cost for an offshore pipeline is quoted to € 1.5 million per km (€ 75 per meter and inch). Corresponding cost for onshore pipelines used by Chalmers in this report seem to fit relatively well with this, for instance five onshore pipeline segments in the Husum-Vasa cluster with diameter between 16 and 20 inches have a cost ranging from € 39 to € 52 per meter and inch depending on distance and volume (discounted to net present value 2012). Europipe also refers to the “more detailed representation” of on- and offshore pipeline cost presented in ZEP (2011) against which Chalmers cost model has been benchmarked (see also Section 6.1). Regarding OPEX, Europipe refers to a fixed cost of € 7,000 per km and year for both on- and offshore pipelines while this report uses 3% of total investments (see Section 3).

Europipe provides few cost data on ship transport. For instance, they do not specify cost for the ship, the liquefaction process, the onshore storage facility or for the offshore discharge process (see Table 3). They do provide a graph showing estimated specific cost per ton CO_2

as a function of ship size and distance. From the graph it appears that specific cost ranges from roughly € 5 to € 10 per ton CO_2 over a distance of 185 km to between € 10 and € 22.5 per ton for a distance of 1,760 km for a ship size of 30,000 and 10,000 m^3 respectively. However, little information is provided on what has actually been included in the cost estimates apart from that the estimates exclude conditioning cost (no definition on conditioning cost is provided, at least not in the part of the report where ship cost is discussed). This makes it difficult to compare with the present work. Nevertheless, some data can be derived from the report such as ship size (10,000 to 30,000 m^3) which is similar to the ship sizes used in this report and the speed of 14 to 15 knots which also is similar to the speed used in this report.

Europipe provides no calculations on the effect on cost from underutilization of pipelines and therefore no direct comparisons can be made with the results provided in Section 6.3. However, they make the same general conclusions that have been made above, namely that underutilization of pipelines will have a substantial effect on cost, that the risk of underutilization is likely to prevent private investors from building oversized pipelines and that building of oversized pipelines probably would require some kind of Governmental involvement, either as sole owner and operator of trunk pipelines or through Public-Private Partnerships (PPP).

The largest pipelines investigated in the Europipe project have a diameter of 48 inches while maximum onshore pressure was set to 150 bar. If this was not sufficient to transport the required amount of CO_2 multiple parallel pipelines are designed. This report applied the same maximum diameter as Europipe, i.e. 48 inches, but lower maximum onshore pressure, 110 bar, based on discussions with the industry.

To conclude; captured and transported CO_2-volumes applied by the Europipe project appear to be high compared to current emission levels as well as to the estimated transport volumes applied above. Little explanation is provided on how Europipe has estimated these volumes. Pipeline routing appears to be merely indicative and does not include collection or distribution systems. Cost estimates for onshore pipelines appear to be based on roughly the same cost levels as in our work while there is a discrepancy for offshore pipelines and little information on cost related to ship transport. Although Europipe does not provide any estimates of the effect on cost from underutilisation of pipelines, they reach the same general conclusions that have been reached in this report, namely that the effect on cost and the element of risk will probably prevent private investors from oversizing pipelines. Thus, if oversized pipelines are to be built, some kind of Government involvement appear to be necessary, e.g. through PPP’s.

6 Discussion

Onshore transport of CO_2 by pipeline has been done in the US at least since the 1970's and, according to GCCSI (Global CCS Institute 2012) there is more than 6,500 km of CO_2 pipelines in operation in the US transporting some 50 to 60 Mt of CO_2 annually. In the Barents Sea in Norway, Statoil has operated a 150 km offshore CO_2 pipeline since 2008 and in 2010 Det Norske Veritas (DNV) published its "Recommended practice for design and operation of CO_2 pipelines". Transport of CO_2 by pipeline is therefore considered as proven technology.

The same applies for ship transport of liquefied and pressurised gases which dates back more than seventy years. Today, ship transport of hydrocarbon gases is a significant worldwide industry. The gas shipping industry has been regulated by a United Nations subsidiary, the International Maritime Organisation (IMO) since the 1960s. The regulation, known as the International Gas Code, or IGC, has supported the industry to a highly satisfactory safety level. The IGC code also covers the transportation of CO_2, allowing some minor relaxations due to the non-combustible nature of the CO_2 cargo, compared to hydrocarbon gases. International regulations for the transportation of CO_2 by ship are therefore well established. In addition, CO_2 shipping is in operation in Europe since the early nineties although only in smaller quantities for the merchant market with vessels in the size of around 1,000 m^3. The ZEP report (ZEP Cost of CO_2 Transport, 2011) mentions that in fact, six LPG/ethylene carriers of 8-10,000 m^3 which could be a suitable size for an early demonstration project are approved also for the carriage of CO_2. Therefore, shipping gases in large volumes is considered proven technology with a long operational record. One area where technology verification is still required is the offshore handling, such as discharge of the cold gas, gas conditioning, connecting to turret and injection.

This report compares the cost of CO_2 transport by pipeline to the corresponding cost by ship for volumes and transport distances relevant to the Baltic Sea region. The work comprises relatively comprehensive analysis of different CO_2 transport systems by pipeline. In order to reach the volumes required for pipeline transport to yield the lowest cost, almost all sources, both in Finland and Sweden, with annual emissions of 100 kt or more had to be included in the three most northerly cluster configurations designed in this report (see Sections 4.2.1 to 4.2.3). It is of course questionable whether capture will be installed on all these facilities in the future, as showed in Section 4.1., since connection lines to a hub may be too costly for some of the plants, of which some may not even exist twenty to thirty years ahead. Furthermore it has been assumed a capture ratio of 85% on all CO_2-streams on each plant. For many of the plants this is likely to render too high capture costs for part of the CO_2 streams (obviously depending on policy measure governing the mitigation). Moreover, half the total CO_2 volume in the four cluster systems identified in Sections 4.2.1 to 4.2.4 originates from burning of biomass for which there are currently no incentives for CCS although this is increasingly being discussed.

Onshore collection systems and onshore semi-spines (large spines connecting the five selected hubs in Sweden) may face considerable local opposition delaying construction and increasing cost. Additionally, for many of the onshore systems it will be difficult to avoid a large number of water crossings which is also likely to add further to cost. If the pipelines have to pass areas with solid basement rock, cost may, according to the industry, increase by a factor ten to twenty, which definitely will render most onshore pipelines economically unfeasible.

All the cost calculations in this report have been based on that all sources connect to the network from day one. This if of course highly unlikely meaning that the alternative to pipeline is either to build several smaller pipelines as the volumes increase, to risk underutilization of a bulk pipeline (spine) for an unknown period of time or to use ship transport, at least until such volumes have been reached that pipeline transport becomes cost wise preferable to shipping. As mentioned in Section 4.3 the effect on cost from underutilization of pipeline capacity is likely to prevent private investors from building oversized pipelines and that building of such pipelines most probably would require some kind of involvement from the Government, either as a sole owner/operator or through risk-sharing in for instance a Public Private Partnership (PPP). However, as indicated on several occasions in this report, this highlights the very obvious advantage Sweden (and Finland) have in the fact that most sources are located along, or very close to the coasts, thus facilitating build-up of CCS transport systems by ship. This is all the more so since ship transport is also estimated to yield lower cost than pipelines, not only for most sources individually but also for most of the relevant cluster configurations. In addition, as indicated above and in Section 4, several factors point to the conclusion that pipeline transport cost estimated in this report may be too low due to terrain conditions (water crossings) and lengthy and difficult permitting procedures which further increases the competitiveness of ship transport.

Nevertheless, one cluster system stands out with regard to pipeline transport: The Oxelösund cluster which comprises several large sources and is located relatively close to the Dalders storage site. For this system, specific transport cost has been estimated to € 12.5. The minimum volume required for pipeline transport to be less costly than ship transport from a hub located in Oxelösund to storage in Dalders was calculated to 4.0 Mtpa in Section 5.1 (see Figure 9). As pointed out in Section 4.2.4 some of the sources included in the Oxelösund cluster will probably select another transport solution than via Oxelösund to reservoirs in Skagerrak or in the North Sea but still there are sufficient large scale emission sources in the region to reach annual capture levels around 4 Mt, as illustrated by for instance the small Oxelösund cluster, also calculated in Section 4.2.4. There are also additional potential sources in the region that may at least share cost on the storage site, like Södra Cell's plants in Mönsterås and Mörrum. It should be noted however, that many of the sources in the region emit biogenic CO_2 so a likely pre-requisite should be that these emissions are incentivized so as to get credits for carbon negatives. The recommended transport solution for the Oxelösund cluster provided storage could take place in Dalders would thus be to utilize ship until volumes have reached the required level where pipeline transport is the least cost transport mode.

In Section 4.2.5 the cost for an onshore and offshore semi-spine connecting the five selected hubs in Sweden was calculated. As indicated in Figure 15, the onshore pipeline will probably be complicated to build for several reasons; all the water crossings that also will have large effect on cost, the potential for multiple local opposition leading to delays and further cost increases and potential cost increases related to areas with basement rock. Therefore, the offshore system appears to be the preferable route. Section 4.2.5 indicates CAPEX around € 6.3 billion and annual OPEX around € 227 million for the offshore semi-spine versus € 6.1 billion and € 212 million respectively for the four separate systems calculated in Sections 4.2.1 to 4.2.4. The four latter, smaller systems however involve many Finnish sources which will obviously complicate the issue (the more sources involved the more complicated the transport system) and the cost differences between the two solutions is well within the margin of error. Furthermore, as stated earlier in this report, there is no need to build a pipeline until volumes have reached the threshold volume where pipeline becomes less costly than ship transport. The CAPEX numbers quoted here constitute a basic reason why CO_2 transport must be regarded as public infrastructure, to be available for CCS project operators to buy required transport capacity at agreed tariffs.

7 Conclusions

The work within Work Package 5 of the Bastor2 project has analysed how a large scale transport system for the Baltic Sea region could evolve over time. The basis has been a detailed geographical mapping of potential CO_2 sources in Sweden and Finland and the assumption has been that transport hubs would be formed on the coast line and at the locations of the five largest emission sources in Sweden and Finland, respectively. Furthermore it has been assumed that clusters of carbon capture sites would develop around these transport hubs and that pipeline feeder systems would bring the gas forward to the hub, for further transport to the storage location. The factual analysis is built on actual distances from sources to hubs and from hubs to two alternative storage locations, on CO_2 emission volumes per site as reported by the emitters and on cost estimation equations as described in this report.

Cost estimation alignment

The model for estimating transport costs, both as capital expense and as specific cost in €o per ton, has for pipeline costs been built on the IEA cost equations and for ship system costs on a proprietary model, aligned with the one used in the Zero Emission Platform (ZEP) Transport Cost report. Considerable adaptation to regional conditions has been made as well as some significant updates of cost element information. The transport costs presented in this report appear to be comparable with those of the ZEP and CO_2Europipe reports, respectively, considering the differences in the baseline scenarios used, such as source volumes and transport distances.

Specific cost for pipeline transport for cluster systems investigated in this work range from € 12.5/ton from Oxelösund to € 20.1/ton from Husum assuming storage in the Dalders structure. Transporting instead the CO_2 by pipeline to Utsira will raise cost significantly, by between 70 and 110%. However, in order to reach the volumes required to achieve these costs, close to all relevant sources will have to be connected to the network, fossil based as well as biogenic.

Cost for transport by ship to Dalders ranges from € 12.5/ton from Oxelösund to € 18.3/ton from Gävle. Extending the transport route to Utsira will raise cost by between 30 and 50% depending on site and volume. However, the calculated cost refers to relatively modest volumes corresponding to CO_2 from single plants in the region. Thus, the calculations performed in this work demonstrate the cost advantage for ship transport during the build-up of a CCS infrastructure when CO_2 volumes are relatively modest.

Nevertheless, and as shown above, the Oxelösund cluster may offer pipeline transport systems to the Dalders storage site with lower specific costs that the corresponding shipping systems, due to the relatively short distance to the storage site and the potential for relatively large volumes of CO_2.

A more general conclusion that may be drawn from the work presented in this report is that transport cost in Finland and Sweden is high compared to transport cost in Continental Europe due to a combination of low CO_2 emissions at individual sources and long transport distances both between individual sources and to potential storage sites. It can also be stated that the same reasoning leads to relatively high pipeline transport costs. In addition, onshore pipelines risk facing considerable complications, technically and economically, related to crossing of lakes, rivers and densely populated areas and also related to obtaining local public acceptance.

Shipping systems present the most attractive prospects

We conclude that shipping systems are for most of the selected hubs and clusters the most attractive transport solution. The main reasons are that shipping for most of the analysed sources/clusters is more cost effective, with specific costs safely below € 15 per ton for the shortest distances, like Slite, Oxelösund and Gävle. It also provides the lowest capital cost in a volume ramp up phase through its higher flexibility and near linear scalability. The capital risk is also lower, through both more flexible capacity utilization and in offering alternative re-deployment of at least parts of the invested capital equipment. It should be underlined though, that technology verification is required for solutions relating to the offshore discharge of CO_2 from ships.

Shipping could simplify the CCS deployment decision making process

With the nature of a shipping system, with comparatively low capital expense and with the possibility of even re-deploying the vessels into another product segment, should the CCS trade be reduced or aborted, thereby offering much lower capital risk than the pipeline business case, CCS deployment could be much facilitated. This could be applicable to four different decision processes:

- In order to finally characterize a geological storage site, CO_2 injection is required, for which case in the offshore situation there appears to be no other realistic transport option than shipping. This could then be a first opportunity to develop a prototype shipping system.

- One or more CCS demonstration projects will be required, to verify technologies along the entire CCS chain, capture, compression/liquefaction, transport and storage. Shipping could for the Baltic Sea region offer opportunities to share cost for certain parts of the supply chain in these projects. Particularly interesting is the possibility to share resources, risk and costs for geological storage if transport to the North Sea could become a viable option, where the geological risk is considered much lower than in the Baltic Sea. Shipping the CO_2 to potential storage sites in the North Sea raises cost by between 31% and 88% for all the ten selected sources except Slite since the relative increase in distance is much greater for the plant on Slite than it is for any other of the selected sources.
- Once having advanced technology deployment through the demonstration phase and characterization of geological storage in the Baltic Sea has been proven, wider deployment could be based on ship transport.
- Should Baltic Sea storage offer less storage capacity than required, CCS deployment could be based on ship transport. This would enable an approach to first use (and possibly deplete) Baltic Sea storage and the turn to storage at an alternative location, likely to be the North Sea.

Pipeline systems could prove cost competitive to shipping in Southern Sweden

The two hubs on the Swedish east coast which may provide sufficient volumes to justify pipeline transport to Dalders are those of Oxelösund and Slite, individually and/or in combination. They are both situated fairly adjacent to the potential storage location in the Baltic Sea (cf Dalders) and could mobilize volumes that justify pipelines over shipping. Specific cost for pipeline transport from clusters located at Oxelösund to Dalders has been calculated to range from € 12.5 to € 17.0 per ton depending on volume in the interval between 4.2 to 13.6 Mtpa and assuming an injectivity of 1.0 Mtpa per well. Therefore, in addition to the above statements about shipping, these two sites could present early opportunities for commercial scale deployment of CCS.

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Tables

Figures

Annexes

Annex 1 Early CCS sites

						Dalders Monocline		Utsira South	
Location	Sector	Total CO_2 (t/a)	Fossil CO_2 (t/a)	Bio CO_2 (t/a)	Captured, tpa	GIS Distance, km	Pipeline Distance, km	GIS Distance, km	Pipeline Distance, km
Raahe	Iron and steel production	3970000	3970000		3 374 500	1065	1172	2299	2529
Porvo	Oil and gas refineries	2930000	2930000		2 490 500	628	691	1862	2048
Meri-Pori	Power & heat production	2814000	2814000		2 391 900	644	708	1878	2066
Vaasa	Power & heat production	1330000	1330000		1 130 500	835	919	2069	2276
Turku	Power & heat production	1640000	1640000		1 394 000	531	584	1765	1942
Oxelösund	Iron and steel production	2170000	2170000		1 844 500	324	356	1558	1714
Luleå	Power & heat production	1990000	1990000		1 691 500	1095	1205	2329	2562
Slite, Gotland	Cement and lime production	1430000	1390000	40000	1 215 500	194	213	1428	1571
Gävle	Pulp and paper production	1330000	10000	1320000	1 130 500	601	661	1835	2019
Husum	Pulp and paper production	1690000	70000	1620000	1 436 500	828	911	2062	2268

Annex 2 Base case transport costs

Specific Transport System Cost - Base case

(€/ton)

(storage)		**Dalders**		**Utsira**	
Base case volume (kt p a)	*Source/ Hub*	*Ship*	*Pipeline*	*Ship*	*Pipeline*
3 374 500	Raahe	14,4	34,2	21,1	77,7
2 490 500	Porvoo	12,2	24,7	19,5	79,7
2 391 900	Meri-Pori	12,4	26,3	19,9	83,6
1 130 500	Vaasa	19,7	64,7	25,4	165,3
1 394 000	Turku	16,0	34,2	21,8	118,9
1 844 500	Oxelösund	12,5	16,6	18,1	84,5
1 691 500	Luleå	17,2	61,5	25,9	137,0
1 215 500	Slite	14,5	15,0	21,8	106,8
1 130 500	Gävle	18,3	47,1	24,2	146,9
1 436 500	Husum	17,3	53,2	22,7	134,6

Annex 3 Comparison Specific Cost to Dalders (5 first sites)

Comparison Specific cost (€/ton)
Raahe to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	22,49	92,45
2,0	15,86	50,84
3,0	15,24	36,28
4,0	13,34	29,12
5,0	13,57	24,93
6,0	12,50	22,23
7,0	12,81	19,33
8,0	12,08	18,05
9,0	12,39	17,13
10,0	11,83	15,59
11,0	12,13	15,10
12,0	11,66	13,99
13,0	11,26	13,07
14,0	11,54	12,88
15,0	11,21	12,15
16,0	11,45	12,08
17,0	11,15	11,47
18,0	**11,38**	**10,94**
19,0	11,11	10,97
20,0	11,33	10,51

Comparison Specific cost (€/ton)
Porvo to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	19,72	54,20
2,0	13,47	29,60
3,0	11,21	21,67
4,0	11,33	16,69
5,0	10,23	14,21
6,0	9,47	12,61
7,0	9,89	11,07
8,0	9,33	10,26
9,0	8,89	9,34
10,0	**9,27**	**8,87**
11,0	8,91	8,23
12,0	8,60	7,95
13,0	8,94	7,48
14,0	8,66	7,09
15,0	8,43	6,93
16,0	8,71	6,61
17,0	8,50	6,35
18,0	8,31	6,25
19,0	8,57	6,02
20,0	8,39	5,82

Comparison Specific cost (€/ton)
Meri-Pori to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	19,8	55,52
2,0	13,5	30,33
3,0	11,2	22,21
4,0	11,4	17,81
5,0	10,3	14,57
6,0	9,5	12,92
7,0	9,9	11,35
8,0	9,4	10,52
9,0	8,9	9,57
10,0	**9,3**	**9,09**
11,0	8,9	8,44
12,0	8,6	8,15
13,0	9,0	7,66
14,0	8,7	7,49
15,0	8,5	7,10
16,0	8,7	6,78
17,0	8,5	6,69
18,0	8,3	6,41
19,0	8,6	6,17
20,0	8,4	5,97

Comparison Specific cost (€/ton)
Vaasa to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	21,1	72,94
2,0	14,7	40,09
3,0	14,2	28,59
4,0	12,3	22,94
5,0	11,2	19,63
6,0	11,6	16,66
7,0	10,8	15,22
8,0	11,2	14,20
9,0	10,6	12,81
10,0	10,1	12,26
11,0	10,5	11,30
12,0	10,1	10,52
13,0	**10,4**	**10,28**
14,0	10,1	9,68
15,0	9,8	9,55
16,0	10,1	9,06
17,0	9,8	8,64
18,0	10,1	8,60
19,0	9,8	8,24
20,0	9,6	7,93

Comparison Specific cost (€/ton)
Turku to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	19,5	46,15
2,0	13,3	25,19
3,0	11,0	17,75
4,0	11,1	14,19
5,0	10,0	12,08
6,0	9,3	10,71
7,0	**9,7**	**9,41**
8,0	9,1	8,72
9,0	8,7	7,93
10,0	9,1	7,53
11,0	8,7	6,99
12,0	8,4	6,57
13,0	8,7	6,34
14,0	8,5	6,01
15,0	8,2	5,75
16,0	8,5	5,61
17,0	8,3	5,38
18,0	8,1	5,19
19,0	8,4	5,11
20,0	8,2	4,94

Annex 3 Comparison Specific Cost to Dalders (5 last sites)

Comparison Specific cost (€/ton)
Oxelösund to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	17,9	28,64
2,0	12,0	15,78
3,0	9,9	11,01
4,0	**10,0**	**8,86**
5,0	9,0	7,38
6,0	8,3	6,47
7,0	7,8	5,78
8,0	8,2	5,28
9,0	7,8	4,87
10,0	7,4	4,56
11,0	7,2	4,28
12,0	7,5	4,07
13,0	7,3	3,86
14,0	7,1	3,70
15,0	6,9	3,55
16,0	7,2	3,42
17,0	7,0	3,33
18,0	6,8	3,21
19,0	7,1	3,11
20,0	7,0	3,05

Comparison Specific cost (€/ton)
Luleå to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	22,56	94,99
2,0	15,92	52,24
3,0	15,30	37,28
4,0	13,40	29,93
5,0	13,63	25,62
6,0	12,56	22,85
7,0	12,87	20,96
8,0	12,14	18,55
9,0	12,45	17,61
10,0	11,89	16,02
11,0	12,19	15,52
12,0	11,72	14,38
13,0	11,32	14,12
14,0	11,60	13,24
15,0	11,27	12,49
16,0	11,51	12,41
17,0	11,21	11,79
18,0	**11,44**	**11,25**
19,0	11,17	11,27
20,0	11,39	10,80

Comparison Specific cost (€/ton)
Slite to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	16,6	17,99
2,0	**10,8**	**9,68**
3,0	8,8	6,87
4,0	7,7	5,46
5,0	7,0	4,58
6,0	7,4	4,04
7,0	6,9	3,58
8,0	6,5	3,26
9,0	6,2	3,01
10,0	6,0	2,81
11,0	6,4	2,63
12,0	6,2	2,50
13,0	6,0	2,37
14,0	5,8	2,27
15,0	5,6	2,18
16,0	6,0	2,09
17,0	5,8	2,03
18,0	5,7	1,96
19,0	5,6	1,90
20,0	5,5	1,86

Comparison Specific cost (€/ton)
Gävle to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	19,6	51,96
2,0	13,4	28,37
3,0	11,2	20,77
4,0	11,3	15,99
5,0	10,2	13,62
6,0	9,4	12,08
7,0	9,8	10,61
8,0	9,3	9,83
9,0	8,8	8,95
10,0	**9,2**	**8,50**
11,0	8,9	7,89
12,0	8,5	7,62
13,0	8,9	7,16
14,0	8,6	6,79
15,0	8,4	6,64
16,0	8,7	6,33
17,0	8,4	6,08
18,0	8,3	5,99
19,0	8,5	5,77
20,0	8,3	5,58

Comparison Specific cost (€/ton)
Husum to Dalders, 1-20 Mtpa

Mtpa	Ship	Pipeline
1,0	21,12	72,35
2,0	14,67	39,76
3,0	14,16	28,36
4,0	12,33	22,75
5,0	11,18	19,47
6,0	11,56	16,52
7,0	10,79	15,09
8,0	11,17	14,08
9,0	10,59	12,70
10,0	10,13	12,16
11,0	10,48	11,21
12,0	10,09	10,44
13,0	**10,39**	**10,19**
14,0	10,07	9,60
15,0	9,78	9,47
16,0	10,05	8,99
17,0	9,80	8,57
18,0	10,04	8,53
19,0	9,82	8,17
20,0	9,61	7,86

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