This document is downloaded from the
Digital Open Access Repository of VTT

Title	Cross-border CO2 infrastructure options for a CCS demonstration in Finland
Author(s)	Kujanpää, Lauri; Rauramo, Joonas; Arasto, Antti
Citation	Energy Procedia vol. 4(2011), pp. 2425-243
Date	2011
URL	http://dx.doi.org/10.1016/j.egypro.2011.02.136
Rights	Copyright © 2011 Elsevier. Reprinted from Energy Procedia. This article may be downloaded for personal use only

VTT
http://www.vtt.fi
P.O. box 1000
FI-02044 VTT
Finland

By using VTT Digital Open Access Repository you are bound by the following Terms & Conditions.

I have read and I understand the following statement:

This document is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of this document is not permitted, except duplication for research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered for sale.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2010) 000–000

Energy Procedia

www.elsevier.com/locate/XXX

GHGT-10

Cross-border CO_2 infrastructure options for a CCS demonstration in Finland

Lauri Kujanpää[a]*, Joonas Rauramo[b], Antti Arasto[a]

[a]*VTT Technical Research Centre of Finland, P.O. Box 1000 (Biologinkuja 5), Espoo FI-02044 VTT, Finland*
[b]*Fortum Oyj, Finland*

Elsevier use only: Received date here; revised date here; accepted date here

Abstract

As the geographic situation of Finland seems to allow no domestic carbon sequestration, cross-border CO_2 logistics is needed. In this paper, the alternative transportation options for CO_2 from a Finnish capture plant case are assessed. The assessment includes selection of the most favourable storage areas, route planning for both ship and pipeline transportation, and cost estimates for both alternatives. An actual CCS demonstration is planned by the proprietor power companies of the chosen case plant, a coal condensing power plant on the coast of Western Finland, giving an interesting opportunity to discuss the results in the light of the current development of the demonstration plant.

Transportation costs are presented for a ship transportation chain from the case plant to the North Sea and for a pipeline running towards the coast of the Barents Sea. The storage areas were chosen because of the potential storage capacity and currently operational injection activities in both regions.

Pipeline transportation is found considerably more expensive than ship transportation as an option for CO_2 transportation from the case demonstration plant to the different storage sites. The levelized costs of shipping the captured CO_2 to the geological formations under the North Sea are estimated to amount to 11,8 €/tCO_2, excluding the costs for liquefaction.

Matching a CO_2 source within EU to a sink outside EU depends on a consistent regulatory framework. In addition to accountability of emissions allowances within the EU Emission Trading Scheme (ETS), the issues include liabilities of CO_2 handling and storage, other legislation both on national and on Community level as well as international maritime conventions.
© 2010 Elsevier Ltd. All rights reserved

Keywords: CO_2; capture; transportation; storage; Finland

* Corresponding author. Tel.: +358 20 722 4617; fax: +358 20 722 7048.
E-mail address: lauri.kujanpaa@vtt.fi.

1. Introduction

The Finnish CCS aspirations earn especial research focus due to their interesting properties that highlight the common logistic and institutional challenges of CCS infrastructure. The main challenges in arranging CO_2 transportation from a source in Finland are a lack of known domestic CO_2 sequestration capacity [1], and distances of over 1 000 – 2 000 km to the closest suitable sequestration sites. Furthermore, some of the most potential CO_2 sequestration sites, i.e. the geological formations under the North Sea, are situated outside the European Union. Despite these challenges, a project named FINNCAP aims at developing a CCS demonstration to the Meri-Pori power plant located in Western Finland by 2015. Meri-Pori is also included as a case plant in a separate research project called CCS Finland (2008-2010), aiming as one of its main objectives to generate a road-map of application of CCS in Finland.

The goal of this paper is to assess the commercially available transport solutions for an early demonstration CCS case plant in Finland. The logistic alternatives are presented and the costs of transportation are estimated for the case plant. The results are then discussed in the light of both the experience gained and decisions made in the designing process of the FINNCAP project. The main interests are the time-frame of system implementation, the viability and the economical acceptability of the cross-border CO_2 infrastructure, when no known domestic or nearby sequestration capacity is available. A potential future CO_2 pipeline infrastructure and long-distance ship transportation are included as options when the CO_2 source-sink matching possibilities are assessed. A general technical description is given of each alternative chain of logistics for the CO_2 to be captured from the case CCS demonstration plant. More over, the current status of CO_2 ship transportation is discussed and chosen logistics system is viewed against a pipeline infrastructure.

2. Case plant description

Meri-Pori power plant, a 565 MW super-critical condensing coal power plant located outside the city of Pori in Western Finland, is one of the most promising industrial installations that plan to apply a CO_2 capture process in the near future. An actual demonstration project, called FINNCAP, plans to capture 50% of the plant’s emissions at full capacity, resulting in emission reduction of more than 1,25 $MtCO_2$ annually. However, in the case study presented here the flow rate of yearly captured CO_2 is assumed to amount to 2,6 Mt/year.

2.1. FINNCAP project

FINNCAP is a project run by the owner companies of the case plant, Fortum and Teollisuuden Voima (TVO), striving for a CCS demonstration in Meri-Pori. The project will seek for funding under the EU CCS demonstration programme. If the demonstration is eventually realized, the CO_2 shall be captured with retro-fit post-combustion technology and transported abroad by ships for final storage in underground geological formations.

Different transportation and storage concepts have been evaluated extensively during the project development. According to feasibility studies, CO_2 ship transportation becomes more economic already for distances exceeding ~300 km in offshore conditions. Ship transportation was also preferred over pipelines because it does not require lengthy permitting process and allows for flexibility with regards to different storage sites. Also different storage options were assessed around the Baltic Sea and North Sea, but offshore storage was found most promising due to opportunities to utilize existing infrastructure, possibilities for offshore unloading and especially local awareness and permitting issues in onshore storage. Storage in oil and gas fields was considered advantageous due to extensive knowledge regarding the geological formations and potential EOR opportunities.

CO_2 ship transportation and geological storage require know-how in significantly different areas than conventional power production. Thus, a partnering approach was adopted to develop the CO_2 transport and storage chain. In late 2009, Fortum and TVO entered into co-operation with Maersk Oil and Maersk Tankers. Maersk Oil is investigating the CO_2 storage concept with EOR opportunities in geological formations in the Danish North Sea, whereas Maersk Tankers is responsible for developing a ship transportation concept to the project. Fortum has taken the overall responsibility of project development and system integration which is considered vitally important for the total project economics.

The project partners have together developed a project implementation schedule which aims at starting the operational phase by the end of 2015. The front end engineering phase is designed for 2010-2011 and the final investment decisions are expected by mid-2012. Detailed engineering and construction is estimated to be completed by mid-2015 after which the commissioning is expected to begin.

3. Assessment of CO_2 transportation options from the case plant

The following assessment of transportation costs and route planning from the case plant to the storage sites are based on work carried out in the CCS Finland -project, and is completely unconnected from the feasibility studies of the FINNCAP project.

3.1. Key assumptions and methods

The design flow rate of captured CO_2 from the case plant is assumed to be 3,0 Mt/year, which is approximately the maximum annual emissions from the facility. On average, the flow rate is assumed to be somewhat lower, 2,6 Mt/year. The flow rates are determined by assuming a highest possible CO_2 capture rate from the case plant. It is important to notice, that these flow rates do not represent the lower CO_2 amounts designed to be captured in the FINNCAP project, run by the owners of the power plant.

System life-time of 30 years is used in all the cost calculations of both ship and pipeline transportation. The economic life-time of a ship investment is however 15 years, after which the ship is sold at 25% remaining value. The rest of the transport infrastructure has no remaining value after decommissioning. Capital costs are calculated as annuities using 8% as the interest rate.

The studied chain of ship transportation includes intermediate storage and loading facilities at the exporting terminal, and an adequate number of tanker ships. The ship terminal itself is assumed to be available for the logistic operations. Additionally, costs of off-loading the liquid cargo are included in order to enhance the comparability between pipeline and ship transportation. Initial pressurization or liquefaction are not included in the presented calculations of either transportation modes, as this cost is typically included in the calculations for the capture facility. CO_2 handling at the receiving terminal is regarded as part of the storage process, and is therefore also excluded from the transportation costs. However, pressure boost to a reasonable injection pressure of 15 MPa is accounted for at the end of a pipeline.

Ship investment costs, estimated as a function of the capacity of the ship, are evaluated based on data from several sources [2-4]. The investment needed for a modular intermediate storage facility is determined using a unit cost given by Aspelund *et al.* [4]. The investment costs for laying down a DN 500 line pipe is assumed to amount to 530 €/m, based on investment data presented by a domestic gas distributing company [5-6]. The given investment cost is used as an average unit value for line pipes of all dimensions. Additional costs due to pressure boost pumps are estimated using the cost data from a CO_2 pipeline calculator by IEA [7]. The material properties of pipelines are determined by following the 5L X-70 specification of the American Petroleum Institute, as suggested by McCoy & Rubin [8].

The pressure drop on a given pipe segment is estimated using the Darcy-Weisbach [9] equation, and assuming an allowed transportation pressure of 8 – 11 MPa. The internal friction factor is explicitly approximated using the Swamee-Jain equation [10]. The energy requirements due to repressurization are calculated using the methodology presented by Koornneef *et al.* [11]. The average viscosity $8{,}817 \cdot 10^{-5}$ Pa·s and density 860 kg/m^3 for CO_2 at the assumed operating temperature (10°C) of the pipeline are given by the Chemical properties handbook [12].

3.2. The studied routes

The closest CO_2 storage potential in aquifers within EU has been stated to exist at least on-shore in the northern parts of Poland and Germany, in southern Denmark and also off-shore in the southern end of the Baltic Sea [13]. The nearest operational CO_2 storage sites to the case capture plant are situated off-shore in the North Sea and Barents Sea. These areas were therefore chosen as the two alternative destinations for CCS logistic operations studied in the CCS Finland project.

A pipeline from the case capture plant to the coast of Barents Sea would range approximately 1250 km, over 400 km more than the longest existing US CO_2 pipeline [9]. Towards the North Sea, a pipeline would have to cross the Gulf of Bothnia into Sweden, continue towards the strait of Skagerrak and onwards off-shore again to the receiving terminal at the west-coast of Norway. The total range of such a pipeline is very close to the on-shore pipeline that would connect the case plant to a terminal on the shore of Barents Sea, consisting of around 800 km of off-shore pipeline and 450 km of on-shore pipeline. However, due to its complexity, it was not seen as a promising route in an emerging CO_2 infrastructure, and was not therefore included in the economic evaluation in the roadmap study.

By ship, the range from the case plant to the receiving terminal off-shore on the North Sea would amount to around 1 950 km one way. Assuming a cruising speed of 30 km/h and on- and off-loading rates of 1 000 tCO_2/h, the journey from the case plant to the destination and back would take over 9 days for a tanker of 40 000 t capacity.

3.3. Cost of transportation

Tanker ships having capacities of 10 000 – 40 000 t of liquid CO_2 are considered in the cost estimations for ship transportation of CO_2. The required intermediate storage capacity at the loading terminal is determined by multiplying the capacity of one ship by a factor of 1,5, as in reality some buffer storage capacity is needed in case of changes in shipping schedules. Extra tank volume is also needed as a headspace for boil-off CO_2. The intermediate storage is assumed to consist of cylindrical heat insulated steel tanks of 3 000 t capacity each, where liquefied CO_2 is stored at the same pressure and temperature, both near the triple point, as during the ship transportation.

Table 1: Estimates for the duration of single round trip from the case plant to the North Sea. The distance for a one-way trip is assumed to be 1950 km. The capacity of the tanker ship is 40 000 tCO_2.

Loading (1 000 tCO_2/h):	40	h
Outward journey:	65	h
Entry and mooring into unloading port or off-shore facility:	7	h
Unloading (1 000 tCO_2/h):	40	h
Return:	65	h
Entry and mooring into loading port:	8	h
Duration in total:	225	h
	9,4	d

Assuming a net draft of 40 000 t per tanker ship, the duration of shipping from the case plant to North Sea area and back is given in Table 1. As the loading processes represent roughly one third of the overall duration of shipping, assumptions made for on- and off-loading flow rates have a significant effect on the resulting quantity of ships required.

Table 2: Transportation costs of CO_2 by ships from the case plant to the North Sea. Here the transportation capacity (2 ships of 40 000 t capacity each) is determined by a design load of 3,0 $MtCO_2$/a, and the costs are levelled using the average load of 2,6 $MtCO_2$/a. Capital costs are based on annuities calculated using 8% interest rate. The economical life is assumed to be 30 years. Cost data is based on sources [2-4].

	Investment M€	CAPEX M€/a	OPEX M€/a	Levelized costs €/tCO_2
Unloading facilities (submerged turret loading)	40	3,6	1,4	1,9
Tankers	130	14,0	7,9	8,4
Loading facilities	3	0,3	0,03	0,1
Intermediate storage	34	3,0	0,5	1,4
In total:	207	20,9	9,8	11,8

Given the assumptions made on ship capacities, loading flow rates and off-shore unloading options, the total levelized cost amounts to 11,8 €/tCO_2 transported. The intermediate storage facilities, and in the presented case, the off-shore unloading facilities have a considerable role in the total costs in addition to ship investments (Table 2).

In order to reduce the head loss due to friction in the pipeline, and thus the number of needed intermediate pumping stations, low flow velocities are preferred in pipeline transportation (Table 3). On the assumed design flow rate, the flow velocity is approximately 0,6 m/s using a pipe with nominal inside diameter of 500 mm. Using the given pipe properties, one intermediate booster pump station is required.

Table 3: Properties for the pipeline from the case plant to Barents Sea.

Type of API 5L seamless pipe:	DN (mm)	500
	Wall thickness (mm)	9,53
	Schedule number	SCH 20
Design flow velocity:	m/s	0,62
Average flow velocity:	m/s	0,53
Length of pipeline:	km	1255
Intermediate boost stations:	number	1

Using the given design and average CO_2 flow rates, the costs amount to roughly 32 €/tCO_2 (Table 4). The costs include the pressurization of the CO_2 to injection pressure of 15 MPa at the end of the pipeline. The share of annual operating costs amounts to below 8 % of the total annual costs.

Table 4: Costs of pipeline CO_2 transportation from the case plant to Barents Sea as estimated in the project CCS Finland. Capital costs are based on annuities calculated using 8% interest rate. The economical life is assumed to be 30 years. Cost data is based on sources [5-7].

	Investment M€	CAPEX M€/a	OPEX M€/a	Levelised costs €/tCO_2
Pipeline	667	59,2	3,4	24,1
Booster pumps	203	18,0	2,8	8,0
In total:	870	77,2	6,2	32,1

4. Discussion

Concerning a possible CCS demonstration at the case plant, ship transportation of captured CO_2 is found more economical compared to transportation by pipeline. This is in line with the conclusion made in the FINNCAP project. Other factors favouring ship transportation were according to FINNCAP project higher flexibility and lighter permitting procedures compared to pipeline alternatives. As the ship transportation of CO_2 is outside the core competence of a power company, it was decided to outsource the handling of the logistics in the FINNCAP project.

What comes to storage site selection, choosing the geological formations under the North Sea as one alternative for where CO_2 could be transported are also in accordance with the FINNCAP project. Based on the experience from the FINNCAP project, the suitability of a storage location is evaluated by the level of knowledge of the characteristics of the particular geological formation and existing infrastructure. Another important factor in the site selection of FINNCAP project was the local awareness and attitudes towards CCS activities and the outlook on permitting processes.

The design of a CO_2 ship transportation chain is highly case-specific. For instance, the required number of ships has a direct impact on the calculated transportation costs. The selected capacities of tanker ships and parameters of loading facilities, mainly regarding maximum flow rates, are among the key issues here. Based on published studies on CO_2-carrying tanker ships [2-4], the ship investment per capacity decreases somewhat on larger ships. Although the largest currently operating water carriers, capable of transporting liquefied CO_2, have capacities of around 10 000 t, larger vessels, at least up to capacities of 50 000 t, are considered to be commercially available [2-3, 14]. The total levelized cost of ship transportation (11,8 €/tCO_2) presented in this paper is somewhat lower than reported for instance in by IEA (USD 15 – 30 for 1 000 – 5 000 km) [14]. However, a direct comparison to literature is difficult, since the system boundaries and assumptions vary from case to case. For example, part of the difference to the results presented by IEA may be explained by the non-inclusion of harbour fees or costs of liquefaction in this paper.

In case of pipeline transportation, the considerable length of the pipeline is a factor driving up the investment and operating costs. The levelised cost for CO_2 pipeline transportation is dominated by the investment cost. The resulting levelised cost (32,1 €/tCO_2 over a distance of 1250 km) can be seen as being within the range of costs presented in literature (USD 2-6 for 2 MtCO_2/year over a distance of 100 km) [14], taking into account the differences in assumptions concerning the pipeline lengths. The rather high cost of CO_2 transportation by pipeline presented in this paper is a result from a very small annual flow rate of CO_2 compared to the high investment cost due to the length of the pipeline.

5. Conclusions

In Finland, the industrial sources of fossil CO_2 emissions are situated mainly along the coastline of the Gulf of Finland and the Gulf of Bothnia. In an early demonstration phase of CCS activities, the CO_2 logistics could be adaptively arranged by long-distance ship transportations. The ship transportation allows flexibility in the system planning, as well as faster application of the CCS operations as compared to CO_2 transportation by pipeline. Under the geographic circumstances of Finland, there is even reason to consider the possibility to base the CCS infrastructure permanently on ship transportation. If affirmative investment decisions regarding CCS demonstrations are met in the Finnish industries faced with a strong need to cut CO_2 emissions, a CO_2 ship transportation ranging approximately 2 000 km one-way would likely be demonstrated as well.

The costs presented in this paper cannot be considered optimized, as they are calculated based on crude approximations using mostly data from the open literature. Moreover, the costs do not include any premium charged by a shipping or a pipeline company, in case the logistics are outsourced. The results do, regardless of the limited data used as input, depict the scale and range of different investment alternatives. Compared to ship transportation, the costs of pipeline investment seem considerably higher for a single case demonstration plant. However, in the light of work carried out in the project CCS Finland, pipeline transportation of CO_2 could become beneficial compared to ship transportation after several emission sources are connected to a trunk line towards the Barents Sea.

Despite the fact that CO_2 ship transportation does not require lengthy permitting processes, there are certain challenges with respect to regulatory development. Ship transportation is currently excluded from the EU ETS and the Monitoring and Reporting Guidelines that have been agreed upon within the EU. Thus, there is a need to extend EU legislation in order to have ship transportation accepted for CCS projects. Also, the ratification process of the London protocol may pose certain challenges for a timely project execution. In addition, the CCS directive needs to be transferred into national legislation and especially long-term liability and site abandonment procedures need to be clarified prior to any final investment decisions by power companies.

Acknowledgements

CCS Finland, coordinated by VTT Technical Research Centre of Finland, is jointly funded by the industries involved and the Finnish Funding Agency for Technology and Innovation TEKES. Additional research contribution to CCS Finland in given by GTK Geological Survey of Finland. The authors would like to thank the Finnish Funding Agency for Technology and Innovation TEKES and participating companies for jointly funding the research carried out in CCS Finland.

References

[1] Solismaa, L. 2009. Suomen merkittävimpien sedimenttikivimuodostumien CCS-soveltuvuus. Arkistoraportti K2.142/2009/56, Geologian tutkimuskeskus. Archive report, Geological Survey of Finland, 23 p.

[2] IPCC, (2005). Special Report on Carbon dioxide Capture and Storage, s. 181-192 (2005)

[3] IEA 2004, Ship Trasport of CO_2, Report Number PH4/30

[4] Aspelund A., Tveit S. P., Gundersen T., 2009: A liquefied energy chain for transport and utilization of natural gas for power production with CO_2 capture and storage - Part 3: The combined carrier and onshore storage, Applied Energy, Volume 86, Issue 6, June 2009, Pages 805-814, ISSN 0306-2619, DOI: 10.1016/j.apenergy.2008.10.023.

[5] Gasum, Press release (March 2009), url: https://www.gasum.fi/tietoamaakaasusta/kaasuverkostot/rakentaminen/Documents/Hameenlinna-Lempaala/2009-04-02_Gasumin_tiedote_vesistonalituksesta.pdf.

[6] Gasum, Press release (January 27th, 2010), url: http://www.gasum.fi/gasumyrityksena/media2/uutiset/Sivut/KangasalaSaarioinenSopimus.aspx.

[7] IEA, 2009: Upgraded Calculator for CO_2 Pipeline systems. Technical Study. Report number: 2009/3.

[8] McCoy S.T., Rubin E.S., 2008: An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage. International Journal of Greenhouse Gas Controll 2 (2008) 219-229.

[9] Chandel M. K., Pratson L. F., Williams E., (2010). Potential economies of scale in CO_2 transport through use of a trunk pipeline, Energy Conversion and Management, Volume 51, Issue 12, December 2010, Pages 2825-2834, ISSN 0196-8904, DOI: 10.1016/j.enconman.2010.06.020.

[10] Menon E. S., Menon P., (2010). Working guide to pumps and pumping stations – Calculations and simulations. Elsevier.

[11] Koornneef J., van Keulen T., Faaij A., Turkenburg W., 2008: Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. International Journal of Greenhouse Gas Controll 2 (2008) 448-467.

[12] Yaws, C.L. (1999). Chemical Properties Handbook. McGraw-Hill.

[13] EU GeoCapacity Project (2009). WP 2 Report – Strorage Capacity. Available online at: http://www.geology.cz/geocapacity/publications/D16%20WP2%20Report%20storage%20capacity-red.pdf1

[14] IEA 2008: CO_2 Capture and Storage, A key Carbon abatement option. International energy Agency.