Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 63 (2014) 2638 – 2644
Energy Procedia

GHGT-12

Ship transport of CO_2 – breaking the CO_2-EOR deadlock

Filip Neele[a]*, Hans Aksel Haugen[b], Ragnhild Skagestad[b]

[a]TNO, Utrecht,The Netherlands
[b]Tel-Tek, 3918 Porsgrunn, Norway

Abstract

The North Sea contains the larger part of the storage capacity in North West Europe. Countries around the North Sea currently focus their attention on developing that capacity for the CCS demonstration projects. It is generally assumed that a second wave of CCS projects will further develop storage in the North Sea. However, a major hurdle is the development of long-distance pipelines. A requirement for the construction of a 'backbone' pipeline is the availability of a sufficient volume of CO_2, with a firm commitment on the duration of supply of CO_2. Especially for EOR purposes a CO_2 pipeline is not attractive, due to continuously decreasing demand for CO_2 after an initial peak. Transport by ship can provide a solution, because of its inherent flexibility in combining CO_2 from several sources, each too small to warrant a pipeline, to one or more storage locations. This paper describes the case for ship transport of CO_2 to North Sea oil fields, especially in the early phases of the development of CCS in Europe, providing the cross-benefit that will increase the lifetime of oil fields and, at the same time, provide the required commercial case for CO_2 capture and transport. This will help develop CCS industry, which will help EU Member States to meet their CO_2 emission reduction targets.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: CO_2-EOR; ship transport; enabling CCS; North Sea.

* Corresponding author. Tel.: +31 88 866 4859.
E-mail address: filip.neele@tno.nl.

1876-6102
Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.286

1. Introduction

CCS in Europe is struggling to build the momentum that is required to reach the scale that is sketched in long-term outlooks, such as those published by the IEA. While there are several CCS projects in the planning phase, aiming at a start of large scale operations in the period 2015 – 2020, the availability of significant volumes of CO_2 in the North Sea in the period 2020 – 2030 is questionable. The combined volumes produced by demonstration projects and, possibly, a few large-scale projects, may not be large enough to construct an offshore pipeline feeding into large-scale storage operations. Such a pipeline could also feed into a number of oil fields that could benefit through CO_2-EOR. The CO_2 demand from these fields represents a potential value of CO_2, which could well be a decisive driver for CCS projects.

Ship transport has the potential of kick-starting CCS, through its ability to combine the output of multiple (and possibly low-volume) CO_2 sources into a single significant and reliable stream of CO_2. This could provide North Sea oil fields with the required certainty of availability of significant volumes of CO_2 within their window of opportunity for EOR. The present uncertainty of supply is widely recognized as one of the key barriers to developing CO_2-based EOR in the North Sea. In addition, carefully designed ships and offshore unloading systems could help avoiding or reducing periods of production standstill needed for reconstruction of offshore platforms/facilities when introducing CO_2 for EOR. Prolonged periods of postponed production are another key barrier to implementing CO_2-EOR offshore.

In this paper we present a possible way forward for CCS in Europe, based partly on ideas for how to overcome important barriers for introducing CO_2-EOR offshore Europe with the large potentials in the North Sea in mind. Symptomatic for the current deadlock situation, major oil companies that have been presented with these ideas tend to recognize their potential but nevertheless hesitate to engage in a project that attempts to confirm the viability of ship transport of CO_2 for EOR. Interest from the Norwegian body Gassnova on the other hand for developing these ideas further, is an encouraging signal that hopefully heralds a change in a more positive direction.

Nomenclature

EOR	Enhanced Oil Recovery
FPSO	Floating Production, Storage and Offloading

2. The case for CO_2-EOR in the North Sea

CO_2-EOR can benefit both the economical and the environmental situation related to oil production. Today, a significant fraction of oil and gas is left in the reservoir when the reservoir is shut down. Injecting CO_2 may give a better utilization of the reservoirs both onshore and offshore. Even a small percentage increase in oil and/or gas extraction leads to significant economic gains for the oil companies. The environmental benefit by EOR is aimed at CO_2 storage, and in particular as an enabler for large-scale storage. If CO_2 is captured from flue gas onshore or offshore, it can be stored at a safe place below the sea surface. By doing this, the atmospheric emissions of CO_2 are reduced. Therefore, a combination of EOR and storage projects would be preferable both from an economical and an environmental point of view.

In North America there is already a long history of utilizing CO_2 for EOR. Currently, CO_2-EOR actually makes up the backbone of the development of CCS in North America.

There are important differences between North America and Europe that at least partly can explain the apparently large difference between these two regions. Firstly, CO_2-EOR onshore as in North America necessarily presents fewer and different challenges as compared to the North Sea region. Another factor is the availability of large and clean natural sources of CO_2 on the North American continent. These sources form a stable supply of large amounts of CO_2, and are only supplemented by a relatively small portion of CO_2 captured from industrial sources. Such CO_2 sources are virtually unknown in the North Sea region, where industrially derived CO_2 would have to form the basis for a CO_2 infrastructure. A third factor is political. While in Europe, with the exception of UK, renewable energy has benefited much from subsidies directed towards specific technologies, in North America such subsidies have been virtually non-existent therefore avoiding preferential treatment. In North America there is also a clear recognition of the vital role fossil fuels play for the society and thus the need to secure their continued use also in a carbon constrained world. This attitude has created the basis for a business case for CO_2-EOR and for CCS. In Europe, with the exception of UK, securing a stable and sufficient energy supply has not been equally high on the agenda. Strangely, even in a petroleum economy like in Norway, securing the future value of petroleum resources and the continued safe use of petroleum through CCS has not been communicated as a rationale for doing CO_2-EOR (or CCS in general for that matter).

The potential for CO_2-EOR in the North Sea has been evaluated several times. NPD (Norway) estimated the technical potential of extra oil from 20 fields that could use CO_2, to be 150–300 million Sm3 of oil [1]. A recent Scottish study by SCCS/University of Edinburgh estimates the total CO_2 storage capacity of all fields in the Scottish part of the North Sea to which CO_2-EOR might be applied to in the order of magnitude of 1000 Mt [2]. The same study indicates that if CO_2 is a cost to projects in the £20–£40 ($28–$56) per tonne range, an oil price of US $80–$110 per barrel will be required to break even.

The cost/benefit of applying CO_2-EOR is of course of vital importance to any oil company. In general, CO_2-EOR projects in the North Sea have so far not been profitable enough to become feasible. This is the result of a combination of several factors:

- Cost of reconstruction of platforms;
- Close-down and delayed oil production leading to negative net present value;
- Cost of CO_2-EOR as compared to other EOR techniques;
- Uncertainty regarding future price of oil.

Add the uncertainty introduced by the lack of stable supplies of affordable CO_2 in the critical periods for oil production and the case for CO_2-EOR at the moment in general terms is non-existent in the North Sea basin, despite the obvious potential for extracting substantial amounts of extra oil.

3. The role of ships for CO_2-EOR

Often, pipelines are considered as the (only) viable transport method for large quantities of CO_2, including CO_2 for EOR. However, ships are competitive for larger distances and smaller volumes.

Although transportation of CO_2 by ship has been common practice for more than 20 years, the purpose of this transportation has not been related to EOR. Up until now, there have only been small tonnage ships (approx. 1000 tons) for supplying CO_2 to the food industry and other relatively speaking, small scale purchasers. CO_2 transportation for CCS purposes will imply different requirements, and there will be other challenges in terms of the design of the ships. The existing fleet is transporting CO_2 with a pressure of around 15-20 bars and a temperature of about -30°C. For larger volumes, the parameters are likely to be around 7 bars and -50°C (near critical point). This may require heating of CO_2 in the ship before offshore offloading, which could represent a major cost factor.

A ship based CO_2 chain may be illustrated as in Fig. 1. While pipeline transportation requires compression up to 80 bar, transportation of liquefied CO_2 requires a liquefaction plant at the source as well as access to quay and loading equipment. At the far end of the chain, unloading equipment must be installed. If the far end of the chain is an offshore oil field, such unloading may take place at the platform itself or at a buoy or another floating installation, often called FPSO.

Ships offer flexibility in the CO_2 chain, a characteristic not possible with pipelines. While pipelines require large capital expenditures up front, this is not the case with ships. Ships on the other hand have higher operating costs. The pros and cons of ships versus pipelines are summarized in Table 1.

It has been shown ([3], [4]) that using ships at an early stage of CO_2 infrastructure development may be feasible. Such flexibility would also be introduced if ships are applied for CO_2-EOR purposes. Ships may then be instrumental in opening up the CO_2-EOR potential in the North Sea. This will be outlined in the following, where the following topics will be outlined in more detail: Ship design and preparation for transport, challenges associated with offshore unloading of CO_2, challenges related to oil fields and platform, and finally, shipping routes including combining ships and pipelines.

Table 1. Ships versus pipelines: Pros and cons.

Pipelines +	Pipelines -	Ships +	Ships -
Low Opex	High Capex	Low Capex	High Opex
Onshore need for compression	Relatively low flexibility	Large flexibility (volume and route)	Onshore need for intermediate storage and liquefaction plants
Can be built both onshore and offshore	Low potential for re-use	Re-use potential	
		Lower sunk cost	
	Large sunk cost		
		Short delivery time	

3.1 Ship design and preparation for transport

CO_2 can be transported under pressure as a refrigerated liquid. Liquid CO_2 has virtually the same properties as water, and can therefore be pumped during loading and unloading. It is a low-viscosity colorless fluid, with density about 1.1 t/m^3, depending on the temperature. At the triple point, liquid CO_2 converts to dry ice.

CO_2 is routinely shipped for commercial use today (food and beverage, cleaning, chemical, fire extinguishers etc.). For these relatively small quantity applications CO_2 is transported in liquid form with a pressure between 15-18 bar and approx. -22 to -28 ºC. For the much larger quantities of full scale CCS transport it will effectively have to be transported near the triple point, i.e. at 7- 8 bara and -50ºC, see Fig. 2.

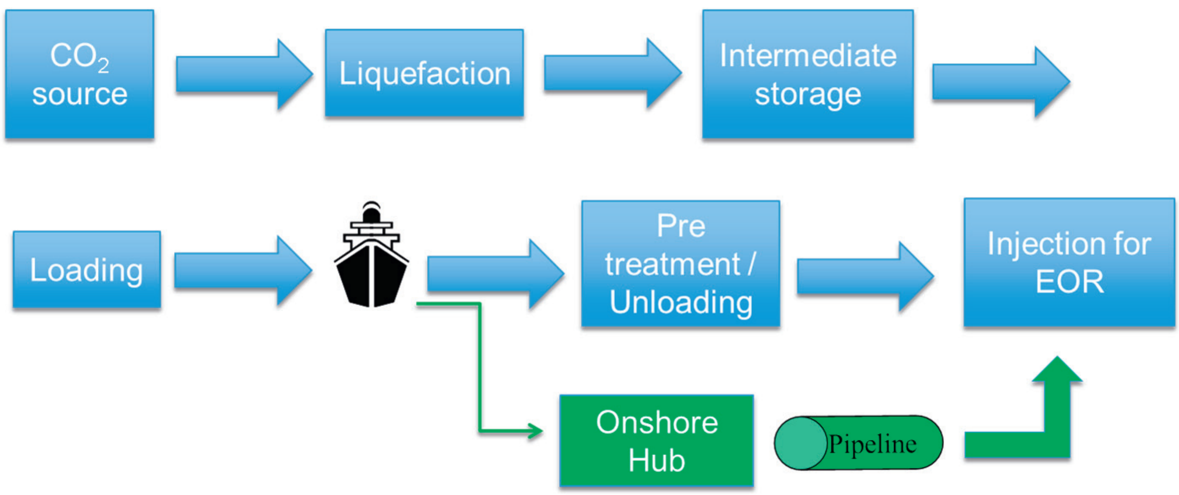

Fig. 1. A ship-based CO_2 chain.

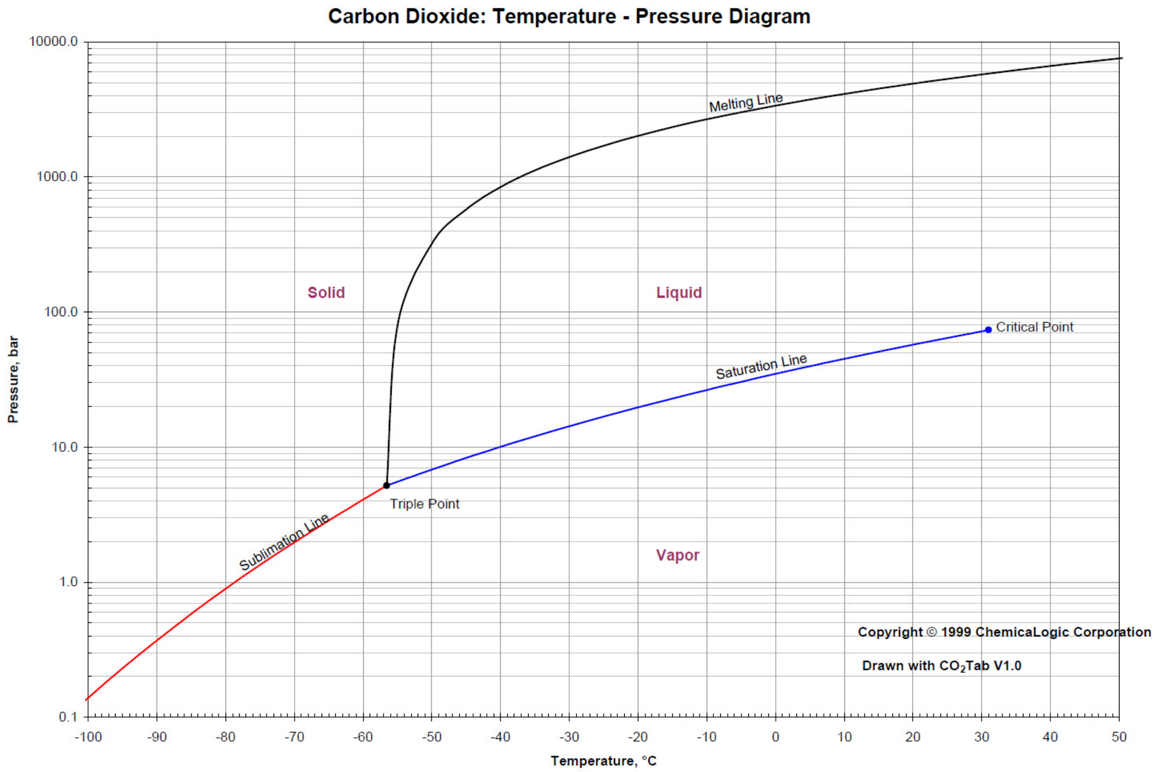

Fig. 2. CO_2 phase diagram

More details on liquefaction of CO_2 can be found in [5], in which a concept for CO_2 transport by ship is presented. Depending on the temperature and the amount of CO_2 there will be a rise in pressure of 0.1 - 0.2 bar/day on board due to thermal leakage. Equipment for decompressing on board is not required for realistic transport distances.

Ship size and tank is yet another issue. Ships in use for commercial transport of CO_2 are only around 1000 t. Larger ships have been proposed and different designs have been proposed, see for instance the study made by the Chiyoda Corporation for the Global CCS Institute in 2012 [6]. In certain studies, ships up to 20,000 tons have been discussed [7]. However, no such tankers have so far been built.

Alternatives to liquefied, refrigerated transport on ships include barge transport and transport of compressed CO_2 in dedicated vessels. Barges may be an attractive option for transporting CO_2 from inland locations to the open sea if suitable rivers or canals are available, but they are not used for CO_2 transport today. Compressed CO_2 is a non-proven option but was suggested by a Norwegian shipping company some years ago.

3.2 Offshore unloading and injection of CO_2 for EOR

Unloading CO_2 in open waters is a particular challenge when it comes to enhanced oil recovery. If introducing CO_2 to an offshore oil field which is not already prepared to receive the CO_2, this would require reconstruction of the platform and shut down of oil production for a prolonged period of time. Net present value estimates in such cases effectively turn such projects unprofitable. Shortening, or better avoiding, the need for oil production shut down may therefore strengthen the case for CO_2-EOR offshore.

There are different possible systems for offshore unloading, which should be reviewed and evaluated with regard to technical and economic feasibility and which could reduce the need for production shut down. Such systems include buoy types including bottom hull buoys and even the possibility of using barges or FPSO.

When injecting CO_2 there are some important requirements as seen from the well and reservoir, related to injection conditions and rates. Injection rates are limited by thermal gradients (cooling and heating of tubing, casing and cement), erosion limits and vibration limits. Some important challenges:
- Thermal or hydraulic cracking in the reservoir due to the large influx of cold CO_2;
- Integrity of the tubing, casing and cement linked to large pressure and temperature gradients along the well;
- The possibility of CO_2 hydrates forming in the near wellbore area, due to the presence of water from the reservoir;
- Water or even dry ice formation at low temperatures;.
- Noise, pulsation and vibration induced by high flow velocities.

The low temperatures in the ship require additional heating and pumping capacity due to the general strict requirements on offloading times. All these restrictions render the operation of transport and injection lines complex and a case to case analysis will be required. Securing satisfactory regularity in the supply of CO_2 is another important issue, but field specific issues will play a role in this respect as well. On a general basis however, some aspects should be mentioned as important areas for further work:
- Selection of materials as a consequence of changes in pressure and temperature during discharge of cold CO_2;
- Design of unloading buoy systems to improve/secure regularity of CO_2 supply to the reservoir also in harsh weather conditions.

3.3 Shipping routes and combination of ships and pipelines

CO_2 may be transported by pipelines or ships only, or by different combinations of ships and pipelines. In [3] this is illustrated; Fig. 3 repeats their illustration. This figure sketches three theoretical outlines for how to transport CO_2 from an number of large CO_2-sources in the Skagerrak/Kattegat area to a defined storage site in Skagerrak.

Similar configurations as in Fig. 3 may be used for transporting CO_2 for EOR at an offshore location. Ships have the undisputable advantage of providing flexibility to the transport system, which the rigid pipeline network cannot match. Depending on volume, distance, number of start-/endpoints, expected lifetime and cost, different alternatives may prove viable in different situations. Designing a ship transportation network will therefore imply a careful evaluation of these factors on a case to case basis. For very large scale scenarios (> 10-20 $MtCO_2$/yr) with a long time perspective, pipelines will likely be the preferred solution, but ships may still provide significant amounts of CO_2 to the system, via one or more hubs located onshore. Hubs may allow for collection of CO_2 from multiple sources by ships, and at the same time securing a stable pipeline transport of CO_2 for EOR to offshore locations.

4. Conclusions

Ships constitute a realistic and interesting alternative to transport of CO_2 by pipelines, even for EOR purposes. In some cases ships may prove to be the only option for the transport of CO_2 to offshore oil fields. The location of the field, the projected duration of CO_2 offtake and the volume of CO_2 may render the case for a dedicated pipeline economically not viable. In such cases, ship transport can offer the required flexibility, in volume, location and timing.

This paper, then, makes a case for a reconsideration of the role of ship transport for the development of CCS in Europe, through its potential as an enabler for CO_2-EOR. Especially in the startup phase of CCS, capture locations in Europe will be few and far between and there will be no case for a large pipeline feeding the CO_2 into the North Sea. Transport by ship is the only viable option to concentrate the CO_2 from the early capture projects into one or more stream of sufficient volume and reliability for oil fields to consider EOR.

Previous studies have developed designs for ships with a capacity of tens of thousands of tonnes of CO_2. The most important remaining technological hurdle is to prove the feasibility of flexible offshore offloading and injection systems, designed to allow rapid conversion of production platforms to handle the additional CO_2 streams.

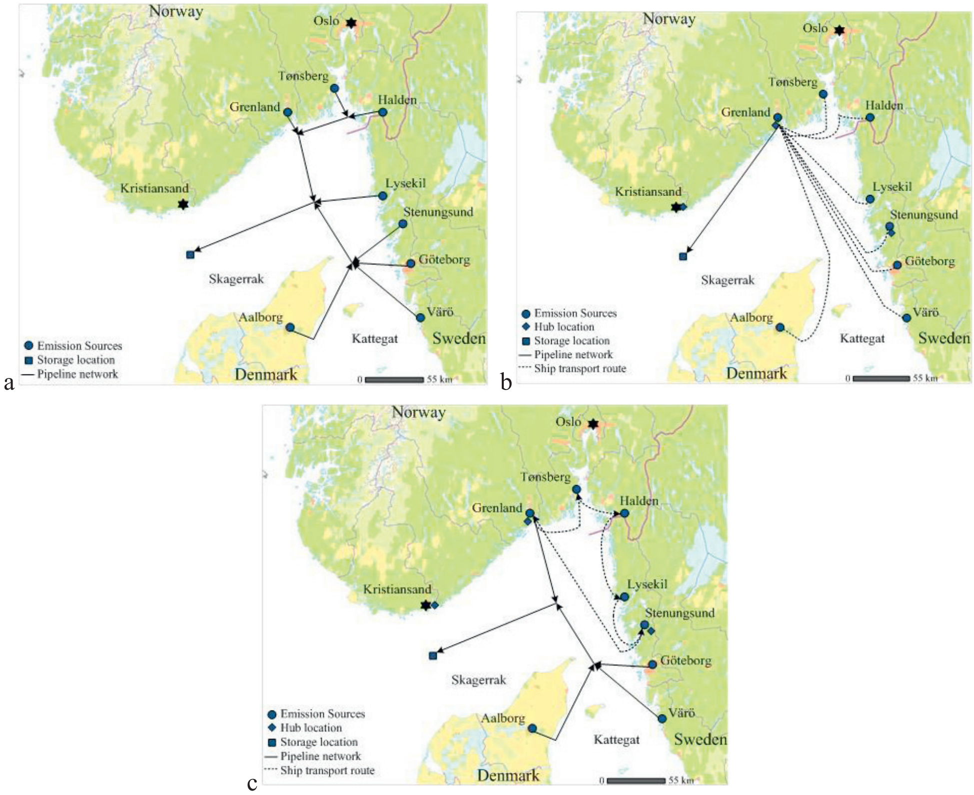

Fig. 3. Illustration of the three main proposed transportation systems for CO_2. (a) Transport pipeline network. (b) Network of ship transport routes. (c) Hybrid network, combining ship routes and pipelines. Figure after [3].

Acknowledgements

The authors thank Gassnova for the permission to use results from a recent project on ship transport of CO_2 in this paper.

References

[1] Scottish Centre for Carbon Storage/University of Edinburgh: Opportunities for CO_2 Storage around Scotland — an integrated strategic research study, 2009. http://www.scotland.gov.uk/Resource/Doc/270737/0080597.pdf.

[2] Norwegian Petroleum Directorate (NPD), 2011. CO_2 Storage Atlas, Norwegian North Sea. http://www.npd.no/Global/Norsk/3-Publikasjoner/Rapporter/PDF/CO2-ATLAS-lav.pdf

[3] Mathisen A, Skagestad R., Eldrup NH, Haugen HA. CO_2 transport solutions in the Skagerrak/Kattegat region. Energy Procedia; 2013; 37; 2949-2956.

[4] Haugen HA, et al.. Infrastructure for CCS in the Skagerrak/Kattegat region, Southern Scandinavia: A feasibility study. Energy Procedia; 2013; 37; 2562-2569

[5] Byeong-Yong Yoo, Sung-Geun Lee, Key-pyo Rhee, Hee-Seung Na, Ju-Mi Park, 2011. New CCS system integration with CO2 carrier and liquefaction process. Energy Procedia 4, pp. 2308-2314

[6] Chiyoda Corporation, 2012. Final report. Preliminary Feasibility Study on CO_2 Carrier for Ship-based CCS (Phase-2 – unmanned offshore facility). Report to the Global CCS Institute. 91 pp + app.

[7] Barrio, M. & al, 2004. Ship-based transport of CO_2. IEA-GHGT 7, Vancouver 2004.

[8] CO_2 liquid logistics shipping concept (LLSC) – overall supply chain optimization, 2011 (http://www.globalccsinstitute.com/publications/co2-liquid-logistics-shipping-concept-llsc-overall-supply-chain-optimization)