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CO₂ MARITIME TRANSPORTATION

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ABSTRACT

The objective of this study is to describe the complete transport chain of CO₂ between capture and storage including a ship transport. This last one is composed by the following steps:

Shore terminal including the liquefaction, temporary storage and CO₂ loading,

Ship with a capacity of 30,000 m³,

On or off shore terminal including an unloading system, temporary storage and export towards the final storage.

Between all the possible thermodynamic states, the liquid one is most relevant two options are compared in the study (-50°C, 7 bar) and (-30°C, 15 bar). The ship has an autonomy of 6 days, is able to cover 1,000 km with a cargo of 2.5 Mt/year. Several scenarios are studied varying the geographical position of the CO₂ source, the number of harbours and the way the CO₂ is finally stored.

Depending on the option, the transport cost varies from 24 to 32 €/tCO₂. This study confirms the conclusion of a previous study supported by ADEME, the cost transport is not negligible regarding the capture one when ships are considered. Transport by ship becomes a more economical option compared with an off shore pipeline when the distance exceeds 350 km and with an onshore pipeline when it exceeds 1,100 km .

KEYWORDS

CO₂; carbon dioxide; transport; ship; costs; energy

1. INTRODUCTION

An answer to climate change is CO₂ capture/transport and storage (CCS). This answer consists in the capture of CO₂ from large point sources emissions and the find of safe place to store it. But source and sink are generally far one from the over. To transport large amount of CO₂, pipeline seems to be the best solution. And a previous study, Bonnissel et al. [2007] designed a supercritical pipeline and gave cost estimation. But transporting CO₂ by ship will be far more flexible and less expensive for long distances. Gas carriers can also be used to collect CO₂ from a number of plants for transport to a central staging post connected to an aquifer by an off shore pipeline. Four existing ships, transporting carbon dioxide for use in industry and alimentary processes have small capacities: between 800 and 1,200 m³.

Few economical studies have been realised including a ship transport, Svensson et al. [2007], Aspelund et al. [2006]. In this last one the complete chain is described including the intermediate storage, loading and unloading systems and the ship. A combined LPG/CO₂ semi refrigerated ship is chosen with a capacity of 20,000m³ under (-52°C, 6.5 bar). A complete energy and cost estimate analysis is performed concluding that the total cost is 20-30USD/tCO₂ for volumes larger than 2 Mt/year and distances limited to North Sea.

This paper presents a complete transportation chain study including CO₂ conditioning, pipeline transport, liquefaction, loading/unloading systems, temporary storages and a new 30 000 m³ ship design. A cost analysis based on three scenarios is also described.

2. TRANSPORTATION CHAIN DESCRIPTION

Capture plants and conditioning

Three flowrates are studied: 1, 2 and 3 Mt/year (this last one corresponding to a coal steam power plant of 600 MWth). For the study, CO₂ is considered free of impurities and water. Two CO₂ sources locations are considered (Fig. 1):

- a source at 100 km fare from the harbour. CO₂ is transported in a supercritical phase by a 15'' internal diameter pipeline. It is delivered at the terminal at 100 bar and at ambient temperature. The gas is available at 1.7 bar with a content of 28% of water after capture, CO₂ conditioning is presented on figure 2 and described in Bonnissel et al. [2007]); The evaluation performed in this study leads to a total cost of € 83 million

for the compression & dehydration process, and between € 78 million and € 90 million for the pipeline.

- a source in the harbour area. CO₂ is delivered at 1.7 bar; 25°C, at the liquefaction stage.

Liquefaction, storage and loading

Between all the possible options of transport we selected two thermodynamic conditions of liquid CO₂: a low temperature to limit tank cost thanks to lower pressure (-50°C, 7 bar) and a high temperature to limit Energy penalty in the liquefaction plant (-30°C, 15 bar). We avoid solid CO₂ transport because of the impact on the loading/unloading operations, solid handling being much more difficult than liquid, especially in case of off shore unloading operation.

The liquefaction

For both sources the liquefaction chain has been simulated using the software HYSYS.

From a bibliographic study and taking into account the new regulations, two coolers are compared in the study: propane and propylene. Two scenarios of cooling are taken into account (Fig. 3):

- CO₂ is first compressed or expanded to reach 7 bar (1 or 2 compressor stages depending on the refrigerant nature) or 15 bar (2 or 3 compressors stages depending on the refrigerant nature) then cooled down to -50°C or -30°C and expanded again to be liquefied.
- 2 cooling loops in serial. The first compressor stage provides a CO₂ at -7°C, which is then expanded down to 30 bar. The second loop cooled down the CO₂ to -30°C and the last expansion is realised to reach 15 bar.

Table 1 summarises the energy required for all these options for a source located 100 km fare from the harbour. It is clear that the options propane, double cooling loops lead to the best scenario. This conclusion is confirmed in case of CO₂ capture in the harbour area.

The temporary storage

To simplify the design and reduce costs, we considered that terminals and ships storage are composed of the same tanks. Storage on terminal is twice the storage on ship. Two designs are possible: cylinder or bilobate (Fig. 4).

The design satisfy the BS5500 PD code. It is realised with the sailing conditions and takes into account the fact that the boil off shall be neither released to the atmosphere, nor relieved. Then a possible pressure increase from 7 to 10.4 for the option (-50°C, 7 bar) and from 15 to 19.5 for (-30°C, 15 bar) and two days of margin in case of bad weather condition are integrated in the design conditions. The design temperature corresponds to the one obtained during a sudden depressurisation and is taken equal to -80°C. This critical temperature governs the choice of the quality of the steel: 3.5%, 5% and 9% Ni; stainless steel 304L and 316L; aluminium 1050. The use of stainless steels and aluminium leads to high thickness and possible construction difficulties. 5 and 9% Ni are the best candidates, 5% Ni being the cost optimum solution and 9% Ni being the weight optimum solution. We chose the 9% Ni which leads to smaller supplying delays and is well known by the manufacturers. The optimal solution is a cylindrical tank in steel 9% Ni, with a casing of 10 mm thick, full of perlite (Fig. 5).

The loading process

In order to transfer the liquefied CO₂ from the temporary storage to the ship, a system of pumps and flexible or rigid arm (piping) is designed. These lines have a diameter of 16" and a length of 120 m. Pressures need to be equilibrated between both storages as the boil off (CO₂ evaporation) generated during the loading operation increases the ship tank pressure. The gas generated is sent back to the liquefaction unit by a second line (Fig. 6).

Ship description

Gas is usually transported under its liquid phase, than means under low temperature. As the ship is specified without any re-liquefaction plant onboard, tanks are designed to resist to the pressure increase.

Specifications for the ship are:

- A capacity of 30,000 m³,
- Process for a loading and unloading with an onshore terminal,
- Pumps with a total power of 5.2 MW, for an offshore unloading,
- Dynamic position for offshore unloading,
- The most economical propulsion in order to reach a speed of 16.5 knots.

- Following the existing regulations: SOLAS (Safety Of Life At Sea), IGC (Ship Carrying Liquefied Gas in Bulk) and MARPOL (MARitime POLution).

Based on these specifications a ship is designed (Fig. 7). 7 tanks, as the one presented previously, are integrated. Cofferdams (600 mm) are placed between the tanks and the front and back parts of the ship in order to limit thermal exchanges and allow inspections. Possible dilatation of the tanks was considered in the design of a new fixing system including wood parts.

Different solutions for the propulsion are considered:

Architecture	advantages	disadvantages
Electric-diesel	Better consumption, architecture optimisation, low power installed	CAPEX high, complexity (higher breakage risk), site coverage consuming
Diesel (type CODAD, COMbinaison Diesel Alternateur Diesel)	CAPEX, well known technology, less breakage risk than electric-diesel	OPEX (higher consumption than electric-diesel)
2T motors	CAPEX, well known technology, OPEX	Pollution, no dynamic position, heavy.

The best option is the electric-diesel but could be considered as too much expensive by the future clients for sequestration operations. Then a more classical architecture like the CODAD type (diesel) is our final choice. Two motors, fed by heavy fuel oil, will be connected to an adjustable blade propeller (Diameter 7 m). The energy necessary on board will be provided by four diesel alternators.

Installation of the different utilities on board is realised in parallel with the stability analysis of the ship. The stability analysis is realised using the software ARGOS with a working load from 10% to 100% (tank full at 95%, keeping a volume for the boil off). It takes into account the new regulations on biologic prevention pollution (ballast are full of water, their loading procedures are described) and the IGC code relative to possible damages. As the ship as an axial symmetry, all the damages are simulated at port on a watertight bulkhead. ARGOS simulations show that IGC criteria are completely respected.

On or Off- shore unloading

- Onshore terminal

This terminal is similar to the loading one. Temporary storage will be twice the one present on the ship in order to have a safety margin, this hypothesis could be optimised integrating the management of a complete fleet of CO₂ ships. Possible reuse of the liquid CO₂ frigories will have to be integrated in a more detailed study.

- Offshore unloading

Between all the possibilities a direct unloading is considered. In order to fit with the constraints: maximum time on place 24 hours in the North Sea, injection power of 5.2 MW for 30,000 m³ of CO₂ at -30°C, 15 bar (Fig. 8). To be able to respected them, 4 wells are necessary to achieve a flowrate of 350 t/h, maximum value tolerated by the aquifer. Conditions imposed at the well head are 0°C and 110bars. Pumps on the ship will furnish the energy to reach 95 bara, the static pressure over the 200 m water depth, will complete it. During this phase, CO₂ temperature increases a bit. To avoid more energy consumption and CO₂ release, CO₂ is naturally heated by thermal exchange between a Bare pipe and sea water, before reaching the well head. To increase thermal exchanges the pipe (X60) is not buried and is only coated against the corrosion. Due to the very low temperature at the inlet of the pipe, some ice will form on external pipe wall over few kilometres. Table 2 summarises different possibilities depending on currents and internal pipe diameter. The optimum between steel mass and pressure drop leads to the choice of a 10" NPS (internal diameter of 10") for a designing pressure of 180 bar. Assuming the minimal external temperature of 6°C (winter North sea), less than ten kilometres are necessary to reach 0°C. Weaknesses of this solution are the embrittlement of the pipe due to freeze/thaw cycles, the sensibility to currents, regulations obliging the burrial of the pipes. Simulations, adding a temporary storage (on plateforme or subsea) have been realised. Such solutions are possible, but with weak points such as the necessity of an high floor space, ballasts and subsea structure appear. Other kind of solutions could be used depending on the existing installations: use of a jacket for mooring, CALM systems (Catenary Anchor-Leg Mooring),etc. CALM buoys are frequently used in offshore industry for the oil offloading of floating production facilities. In TransCO₂ case, CO₂ carrier is moored to the CALM buoy the liquid CO₂ is transferred from the carrier to the injection network with floating hose. For this solution there is a need for development concerning low temperature and

high pressure flexible. A solution without mooring structure can be envisaged but required a dynamic positioned (DP) vessel. This kind of vessel is equipped with thrusters ensuring the perfect positioning of the vessel over the injection location. DP vessels are commonly used for the installation of subsea pipelines and drilling rig, but they are fuel consuming degrading the carbon balance of the CO₂ transport. These solutions are compared in the following table:

Mooring type	advantage	weakness
No mooring structure	Vessel with dynamic positioning	fuel consuming CO ₂ emission Weather dependant
CALM system	control of ship position weather independent Well known technology	Mooring assistance Space consuming
Disconnectable mooring plug	control of ship position weather independent self governing mooring	
Jacket	control of ship position weather independent Re use of existing structure	Costly if new Mooring assistance

3. SCENARIOS

The basic harbour is composed of

- liquefaction part: centrifugal compressors, plate heat exchanger, vertical centrifugal pump (high flow rate, axial flux), cooler boxes and additional pumps.
- storage: 14 tanks, lines between storage (on terminal or on ship) and liquefaction unit (boil off treatment), flexible or rigid arm, transfer pump.

Depending on the scenario, functionalities on the harbour will be adjusted.

Three scenarios are compared (Fig. 9):

1. 2 harbours A and B, B having a direct connection by pipe (200 km) to an off shore aquifer. A liquefaction unit is present on B.

2. 2 harbours A and B, there is no liquefaction unit on B. Then ambient temperature of the CO₂ coming from the on shore pipe and directly connected to the off shore pipe is used to heat the CO₂ coming from the ship.
3. 3 harbours A, B and C. A and B correspond to the basic case, C is connected to an off shore aquifer by a pipe and doesn't have a liquefaction unit. These last case could be representative of a French, English and Dutch case.

4. COST ESTIMATE

An economical study is performed on the scenarios previously described. For this estimation the complete transport chain is considered: conditioning of the CO₂ at the outlet of the capture unit (only dehydration and compression), 100 km on-shore pipe in supercritical conditions (180 bar), liquefaction unit, temporary storage, ship transport covering 1,000 km, unloading in an offshore pipe for final storage. Economic depreciation is supposed to be 5% over 30 years. Costs for the conditioning and the on shore transport are based on a previous study supported by ADEME (Bonnissel et al., 2007). and based on Chauvel cotations (Chauvel, 2003).

For both solution (-50°C, 7 bar) and (-30°C, 15 bar), the total cost (CAPEX and OPEX) of the installations from the outlet of the capture plant to the inlet of the temporary storage (conditioning, transport and liquefaction) showed that the (-30°C, 15 bar) case was the cheapest one. Then scenarios were estimated only for this option.

For the liquefaction the case (-30°C, 15 bar) and 2 cooling loops is considered.

Transport chain	description	Cost M€/year (Economic depreciation 5% over 30 years)	Source (Year price)
CO2 conditioning	Dehydration, compression	18	2005
On shore transport	On-shore pipe	9	2005
Liquefaction unit	Compressors, heat exchangers, pumps...	4	2005
Storage	14 tanks	7.1	2007
Loading/unloading	Pump, loading arm, transfer lines	negligible	
Ship	Ship with 7 tanks	39.3	2008
Injection	Heating, heat exchangers, pump Subsea flow line	13	2008

Figure 10 present costs obtained for the three scenarios. Ship transport represents the most expensive part in the chain. However all the expenses linked with a normal ship exploitation are taken into account within this cost i.e. the one of the ship, the expenses for her maintenance, the crew, tax, insurance, harbours ... The conditioning part is under estimated as it is composed in our examples of only the dehydration and the compression units. In reality, impurities will have to be treated too, increasing the final cost of the conditioning part.

Respectively for the scenarios 1, 2 and 3, 24 €/tCO₂, 22 €/tCO₂, and 32 €/tCO₂ are obtained. This confirms that transport cost is not negligible when it integrates a ship part.

A comparison between ship transport and on or off shore pipe is performed. Depending on the CO₂ quantity, more than one ship can be considered. CO₂ source is considered to be in the harbour area and then only the CO₂ conditioning, liquefaction and storage are considered. Cost for the pipe onshore are those considered in the previous study (Bonnissel, 2007). Figure 11 presents the results of this comparison. 4 quantities of CO₂ are simulated (0.8; 1.6; 2.8; 5.6 Mt/year). Discontinuities of the lines are due to the fact that only a whole number of ships can be added. Clearly our 30,000 m³ ship is over estimated for the 0.8 Mt/year and at least two ships are necessary to transport 5.6 Mt/year. Then compared to a pipeline ship is a more economical solution when distance between two harbours exceed about 1,100 km (onshore pipe comparison), and exceed 350 km compared to an offshore pipeline (export towards an offshore aquifer).

5. CONCLUSION

Ship transport is a flexible alternative to pipeline for an offshore storage option, even for a harbour to harbour transport. It can be cost attractive for long distances (350 km for an offshore storage, 1,100 km for a coast to coast case). Compared with the pipe option. This technical-economics study shows the feasibility to build and use a 30,000 m³ ship to transport CO₂ under (-30°C, 15 bar). Cost estimation leads to a transport cost from 24 to 32 €/tCO₂ covering the chain from the capture outlet to the injection in an offshore aquifer.

ACKNOWLEDGEMENT

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FIGURES CAPTION

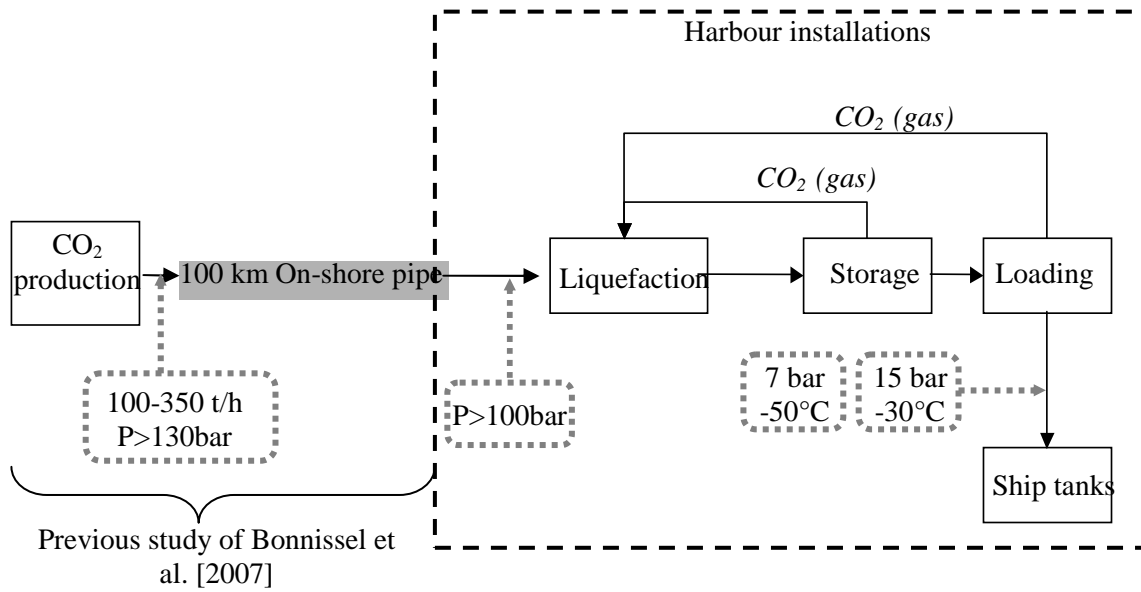


Figure 1: Basic cases

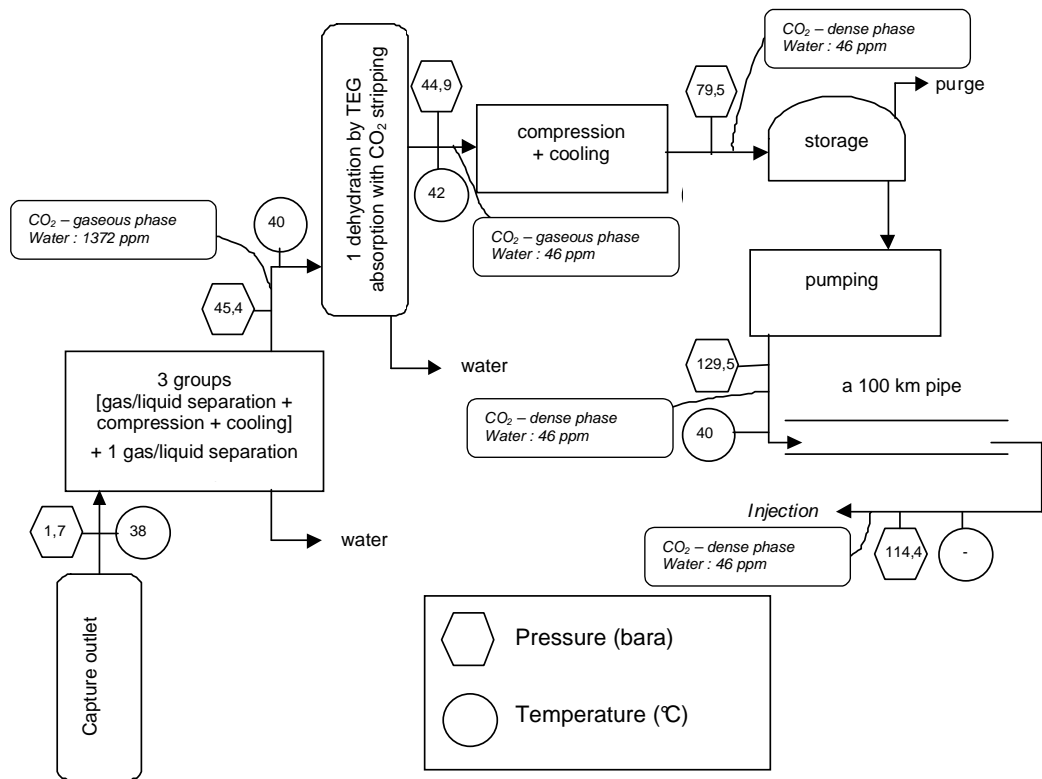


Figure 2: Process flow diagram for the dense phase case

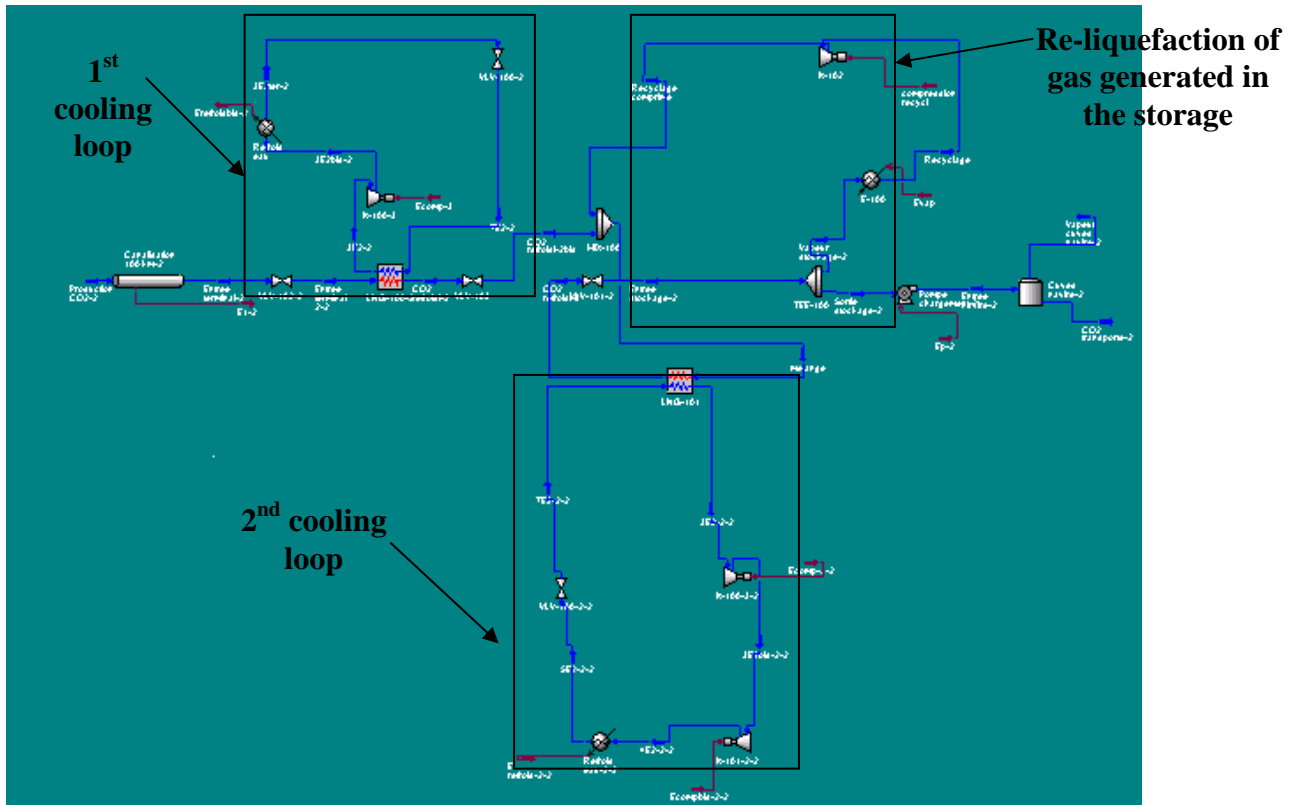


Figure 3: Liquefaction unit

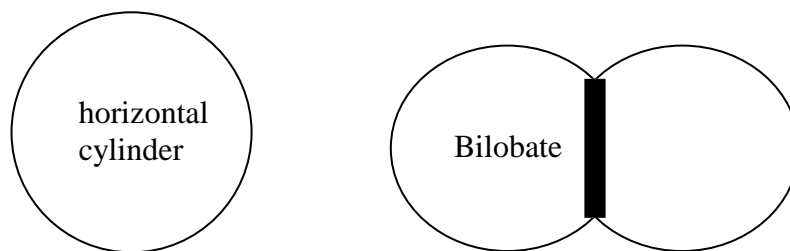


Figure 4: Possible tanks for CO2 temporary storage.

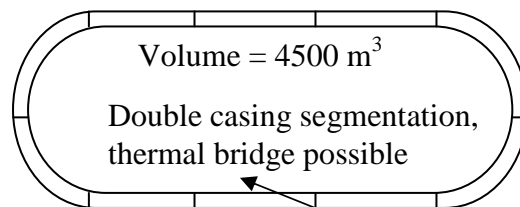


Figure 5 Intermediary storage characteristics. A 4500 m³ tank composed of a double casing containing Perlite vacuum packed (thickness 30 cm), having an external diameter of 14.7 m for 32.3 m length.

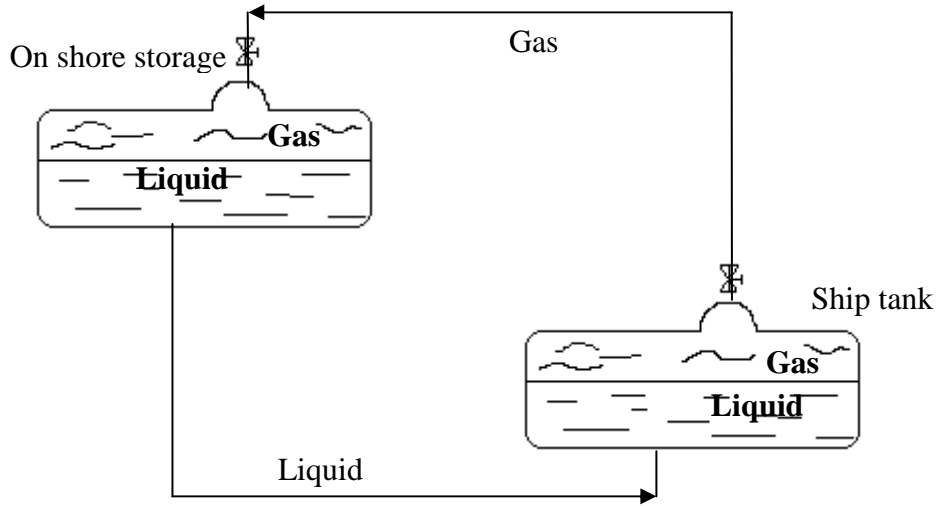


Figure 6: Boil off management during the loading process.

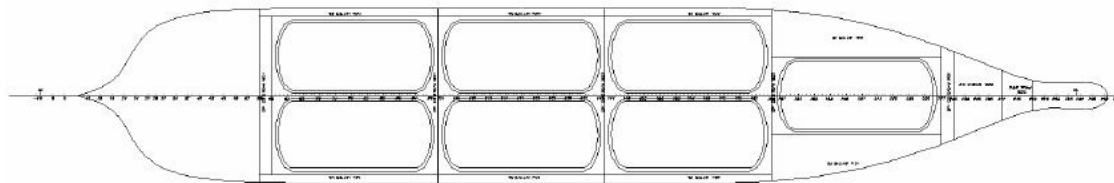
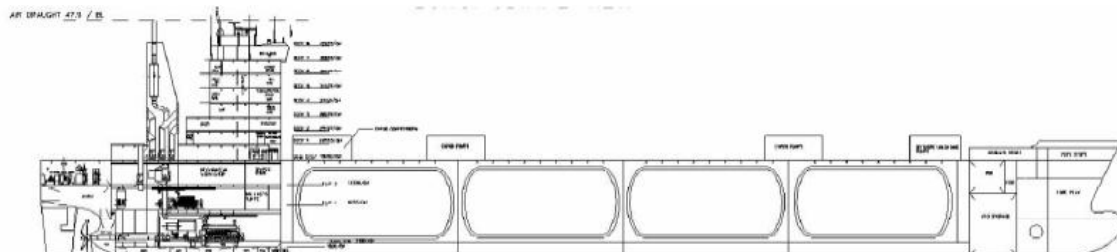


Figure 7: Typical arrangements for a CO2 ship.

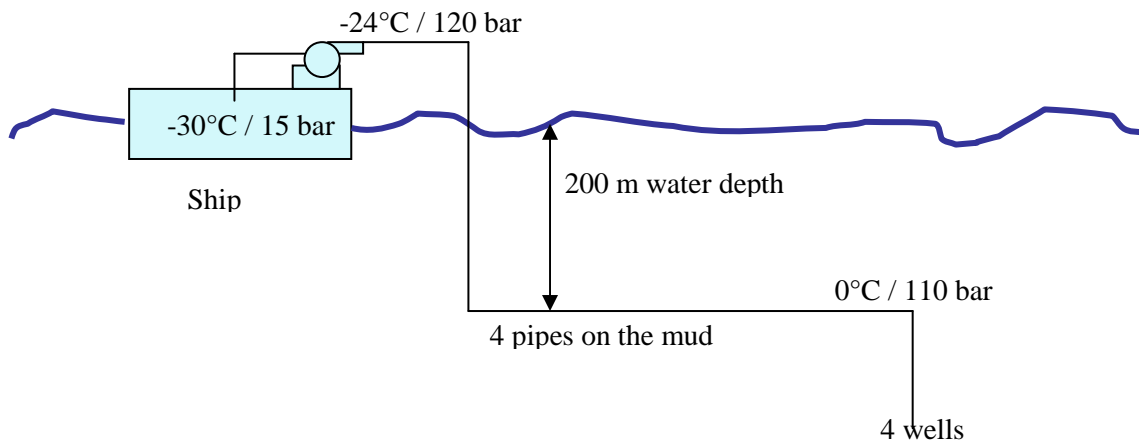


Figure 8: Offshore unloading

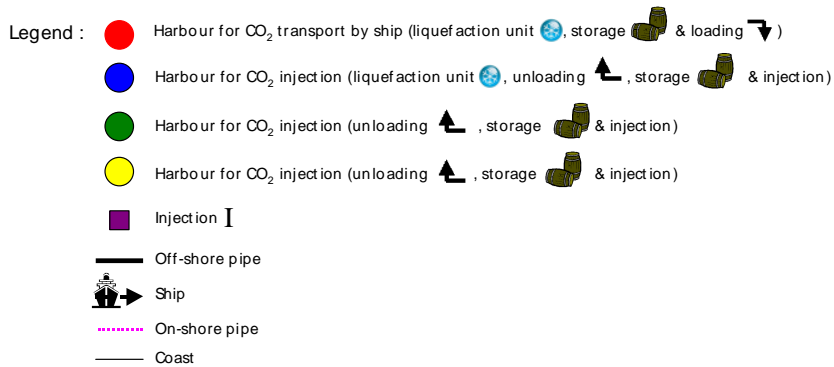
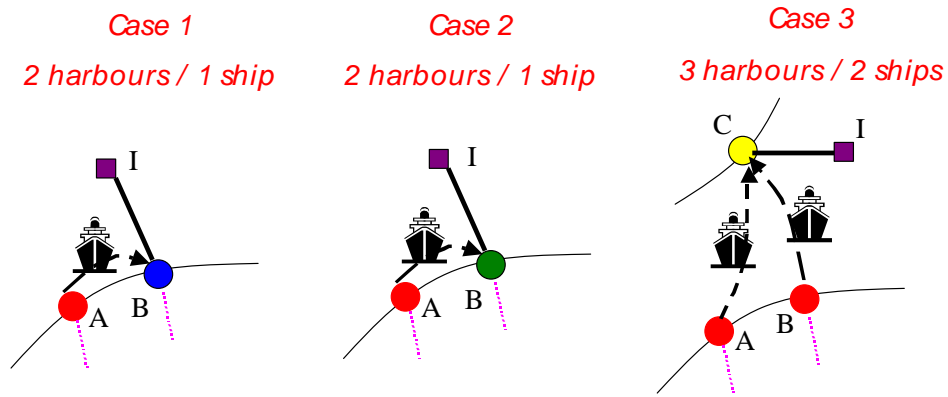


Figure 9: Use cases

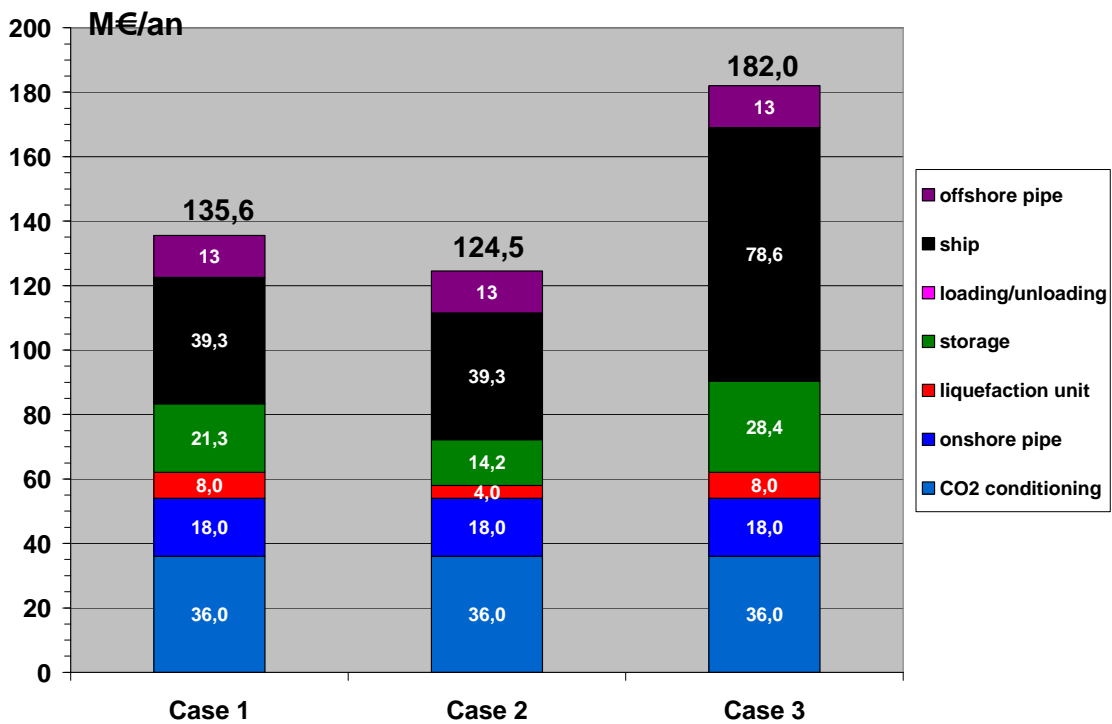


Figure 10: Scenarios costs evaluation

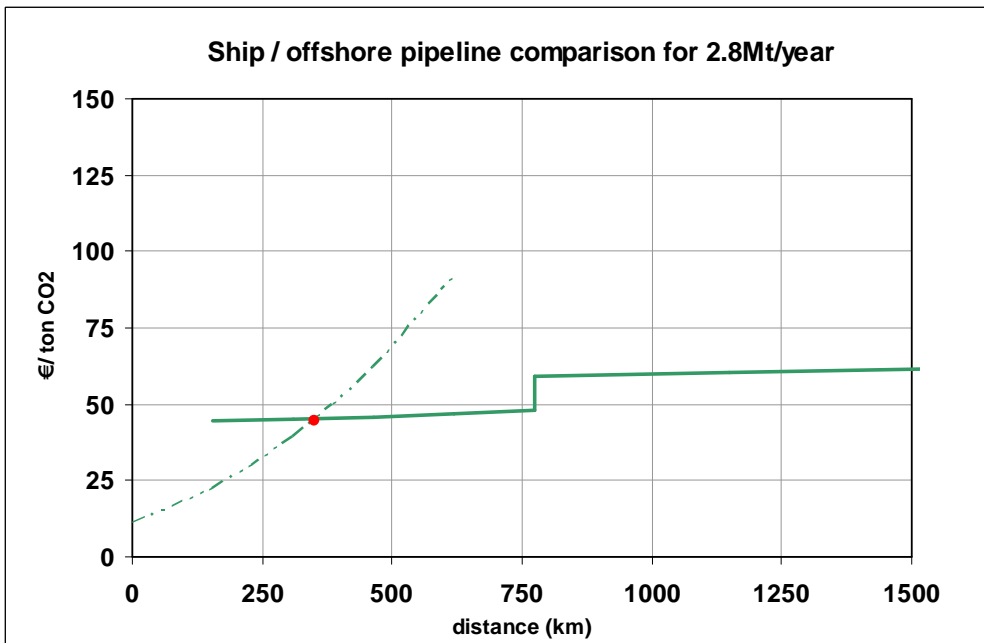
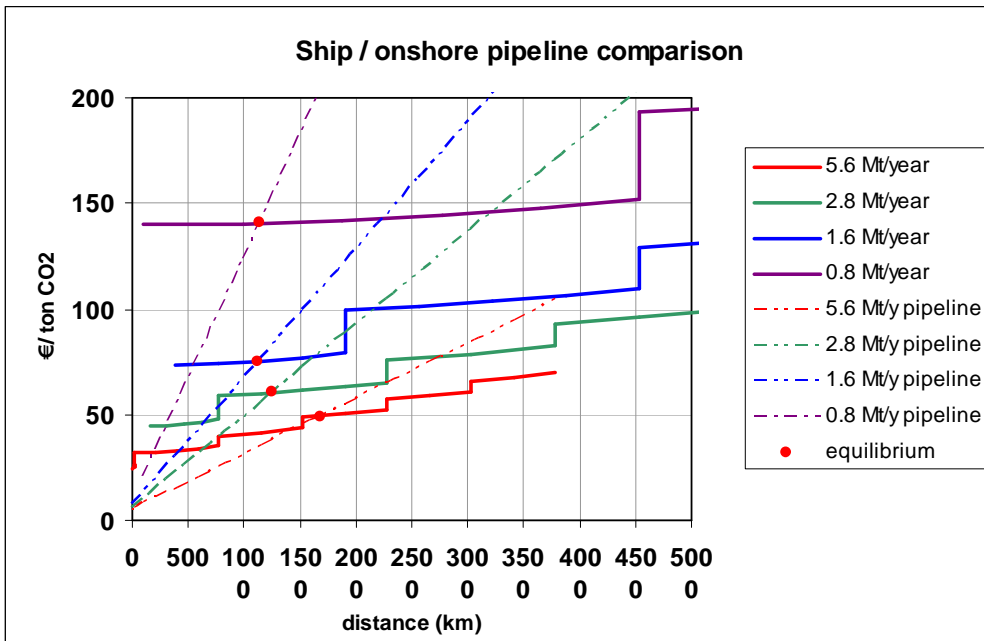


Figure11: Ship/pipeline comparison

TABLES

CO ₂ flow rate = 350 t/h		-50 °C / 7 bar	-30 °C/ 15 bar	-30 °C/ 15 bar	-30 °C/15 bar
Fluid cooling loop		20% ethylene - 80% propylene	20% ethylene - 80% propylene	100% propane	100% propane
Nature (% mass.)					
Flow rate (t/h)		193	216	143	147
Compressor power					
CL1	Stage 1 (MW)	<i>from 1.4 to 3.7 bar</i> 4.4	<i>from 3.1 to 8 bar</i> 4.6	<i>from 1.3 to 3.7 bar</i> 3	<i>from 3.25 to 9.75 bar</i> 1.8
	Stage 2 (MW)	<i>from 3.7 to 9.5 bar</i> 4.6	<i>from 8 to 21 bar</i> 4.7	<i>from 3.7 to 10 bar</i> 2.9	
	Stage 3 (MW)	<i>from 9.5 to 24 bar</i> 3.9			
CL2	Stage 1 (MW)				<i>from 1.3 to 3.6 bar</i> 1.1
	Stage 2 (MW)				<i>from 3.6 to 9.8 bar</i> 1.1
CO₂ Pump power (kW)		34	36	36	36
Energy					
Energy for liquefaction (kWh/tCO ₂)		37	27	17	12
		(kJ/kg) 133	96	61	42
Upstream energy* (kWh/tCO ₂)		94	94	94	94
		(kJ/kg) 338	338	338	338
Total energy (kWh/tCO ₂)		131	121	111	106
		(kJ/kg) 471	434	399	380

Table 1: For a source at 100km from the harbour, energy required from the different options.

(* Energy for dehydration and compression before entering the 100 km pipeline)

	Solution with 4 injection lines							
flow rate per well (bpd)	49528	49528	49528	49528	49528	49528	49528	49528
External current velocity (m/s)	0.005	0.5	0.005	0.5	0.005	0.5	0.005	0.5
Pump outlet temperature (°C)	-22	-23	-23.7	-24.2	-24.2	-24.4	-24.4	-24.5
Internal diameter (")	8	8	10	10	12	12	14	14
Pressure drop (bar)	21.0	9.0	6.2	2.4	2.2	0.7	0.9	0.3
Subsea pipe length (km)	7	3	6.5	2.5	6	2	5.5	2
Ice deposition length (km)	3		3		3		2.5	
Injection temperature (°C)	0.1	-0.4	0.0	-0.6	0.0	-1.6	-0.1	-0.3
CO ₂ velocity (m/s)	2.8	2.8	1.8	1.8	1.2	1.2	0.9	0.9
Steel mass (t)	671	288	974	375	1295	432	1616	587
Pipe volume (m ³)	908.0	389.2	1317.4	506.7	1751.2	583.7	2184.9	794.5
Topside pump power (MW)	5.43	5.55	5.18	4.76	4.73	4.58	4.59	4.53

Table 2: Pipe length necessary to reach the injection conditions.