Costs benchmark of CO_2 transport technologies for a group of various size industries

Simon Roussanaly[a,*], Gaelle Bureau-Cauchois[b] and Jo Husebye[a]
[a]SINTEF Energy Research, Sem Sælandsvei 11, NO-7465 Trondheim, Norway
[b]Geogreen, 7 rue E. et A. Peugeot, 92563 Rueil-Malmaison Cedex, France
* Corresponding author. Tel.: +47 735 93 767; fax: +47 735 97 250; E-mail address: simon.roussanaly@sintef.no .

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Abstract

This paper summarizes key results from the Collaborative COCATE Project for the European Commission (FP7). The costs of transporting a total of 13.1 MtCO_2/y from small- to large-scale emitters around Le Havre (France), to Rotterdam (Netherlands) via onshore pipeline or shipping are evaluated. Sources send emissions to five CO_2 capture centres, which are then linked via a 40 km long collection network to deliver the treated CO_2 to the point of export. This network was designed to accommodate peak flow rates and multiple network designs were considered for the various export scenarios evaluated in the study. The economic evaluation established that conditioning CO_2 at the cluster level, rather than at the point of export, and transporting it in dense phase was the most cost-effective solution for both export systems. As for exporting the CO_2 from Le Havre to Rotterdam, the evaluation highlighted three potential transport solutions: either onshore via one 24" or one 28" diameter pipeline or offshore using three ships with effective capacities of 30,000 m^3 each. The onshore pipeline options proved to be 10 % cheaper than the shipping scenario. Sensitivity analyses confirmed that the onshore options remained the best choice.

Keywords: CO_2; Transport; CCS; Costs Benchmark; Costs evaluation; Pipeline; Shipping; Pooling network; Cluster;

Abbreviations: NPV of costs, net present value of costs; CAPEX, capital expenditures; OPEX, operating expenditures; CCS, carbon capture and storage; KPI, Key Performance Indicator;

1. Introduction

CO_2 capture and storage (CCS) has been identified as a potential technology to reduce anthropogenic CO_2 emissions. According to projections (Herzog, 2011; Rochelle, 2009), CCS is expected to account for 20 % of the man-made greenhouse gases emissions reduction in 2050 with one of the lowest cost. Among the factors affecting the attractiveness of CO_2 sources for CCS, the IPCC Special Report on CCS (Metz et al., 2005) highlights four parameters: CO_2 volume, CO_2 concentration and partial pressure, integrated system aspects and proximity to suitable reservoir.

So far, most R&D projects in the CO_2 transportation field have been exclusively focused on the CO_2 emitted by power plants having their own CO_2 capture process. Only few projects consider combining multiple CO_2 sources from small- to large-scale to obtain a large CO_2 volume. Indeed, while major industrial facilities can be fitted with their own CO_2 capture and transport installations, this does not apply to units that emit less CO_2 –from a few tens of thousands to several hundred thousand metric tons per year– and for which the investment required would be uneconomic on a stand-alone basis. In order to cut costs and to make CCS an affordable technology, these sources must send their flue gases to a cluster where CO_2 is captured and share a transportation system. As one of the first projects dedicated to the issue of pooling CO_2 transport, COCATE allows various size CO_2-emitting industrial sites located in the same geographic area to cut their CO_2 emissions in the same way as major industrial facilities. The objective of COCATE is to analyse the conditions for transporting the flue gases emitted from several CO_2-emitting industrial facilities organized in capture clusters, and for exporting large quantities of captured CO_2 to storage areas. In COCATE, a specific case is studied: the industrial basin of Le Havre (France) exports its CO_2 emissions to a hub located in Rotterdam (Netherlands) from where CO_2 is sent to several potential storage sites.

In this paper, our objective is to benchmark onshore pipeline and shipping to transport CO_2 from a group of 13 mid-size industries from Le Havre area (France) to Rotterdam (Netherlands). Different options to pool and transport CO_2 from Le Havre to Rotterdam are assessed for a designed capacity of 15.45 $MtCO_2/y$ and annual emissions of 13.1 $MtCO_2/y$[1]. Among these options, the cost-efficient ones are pointed out to obtain the optimal pipeline and shipping supply chains. The two cost-optimized transport options by onshore pipeline and shipping are then compared and submitted to sensitivity analyses on energy prices, discount rate and project duration to determine the most cost-efficient technology for the COCATE project.

2. System boundaries and technical options

2.1. System description and boundaries

2.1.1. Transport supply chains

In the COCATE project, CO_2 is considered to be purified before the transport from Le Havre (France) to the onshore harbour of Rotterdam (Netherlands) where CO_2 is reconditioned to be sent and injected in North Sea offshore fields. To reach Rotterdam, CO_2 can be transported using different export systems: onshore pipeline, offshore pipeline and shipping.

The pooling of flue gases and the post-combustion capture centres are not detailed in this paper. The inlet of the supply chain is almost pure CO_2 (out of an amine-based capture process), at atmospheric conditions, coming from capture units located in five clusters. CO_2 coming from these clusters needs first to be gathered, conditioned and transported within Le Havre, to a common hub depending of the export system. This part of the transport supply chain is called the CO_2 collecting network and is around 40 km long.

The hub location and its requirements depend on the option chosen for the export system. The pipeline hub must be located in the eastern part of Le Havre (the onshore export pipeline is planned to link Le Havre to Rotterdam), avoid important elevation changes and should not be located in an area banned from an environmental perspective. The ship hub must be located in the western part of Le Havre, have an access to water, be in a non-tidal zone, offer enough surface area to build storage capacity and should not be located in an area banned from an environmental perspective. The description of the CO_2 collecting networks and the location of the pipeline and the ship hubs are depicted in Figure 1.

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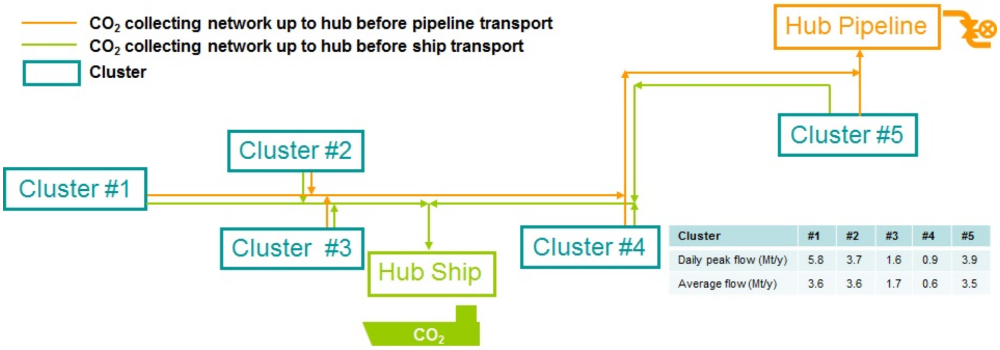
[1] For comparison, the coal power plant included in the project emits 4 $MtCO_2/y$ with a peak flowrate of 6.5 $MtCO_2/y$. This peak flowrate corresponds to an electricity production of around 1 GWe.



Cluster	#1	#2	#3	#4	#5
Daily peak flow (Mt/y)	5.8	3.7	1.6	0.9	3.9
Average flow (Mt/y)	3.6	3.6	1.7	0.6	3.5

Figure 1. Illustration of the CO_2 collecting network organization

Depending on the export system, the CO_2 characteristics required at the hub are not the same. At the outlet of the pipeline hub, dense CO_2 at 150 bar and 25 °C is necessary (Aspelund and Jordal, 2007). Hence CO_2 can be directly sent to the export pipeline. The conditioning before pipeline transport consists of compression stages and pumping, combined with the removal of unwanted components (dehydration). In order to reach the pipeline hub, CO_2 is conditioned at the cluster level and transported up to the pipeline hub from where it feeds the export pipeline after either pumping (when transported in dense phase in the collecting network at an inlet pressure of 110 bar and a temperature of 25 °C) or after additional compression steps and pumping (when transported in gaseous phase in the collecting network at an inlet pressure of 9 bar and a temperature of 25 °C).

At the outlet of the ship hub, liquid CO_2 at 6.5 bar and -50.3 °C is required (Aspelund et al., 2006). Hence at the ship hub, CO_2 can be stored in cryogenic buffer tanks, ready to be loaded on ships. The conditioning before shipping consists of compression stages and of a liquefaction process using ammonia cooling cycles (Alabdulkarem et al., 2011; Aspelund et al., 2005), combined with the removal of unwanted components (dehydration).To reach the ship hub CO_2 is conditioned at the cluster level and transported up to the ship hub from where it is either directly stored (when transported in liquid phase in the collecting network at an inlet pressure of 8 bar and a temperature of -50 °C) or further conditioned before storage (when transported in gaseous phase in the collecting network at an inlet pressure of 20 bar and a temperature of 25 °C or at an inlet pressure of 3 bar and a temperature of 25 °C).

Regarding the export systems transporting the CO_2 from Le Havre hubs to Rotterdam, three technologies are possible: onshore pipeline, offshore pipeline and shipping. However a preliminary study has shown that transport by offshore pipeline is 30 % more expensive than the onshore pipeline options as the offshore pipeline is only 100 km shorter than the onshore one. In addition, a third party access is easier to achieve when considering onshore pipelines. Therefore even though offshore pipeline may be interesting if social acceptance or risks are issues, this option is not presented in this paper. The characteristics of the onshore pipeline and shipping export systems are described below and their corridors are presented in Figure 2. It is important to note that in both cases, CO_2 in Rotterdam is reconditioned to meet the inlet requirements of an offshore pipeline, 200 bar and 25 °C (European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2011). Even though the transport after Rotterdam and the injection in North Sea fields is not part of this study, it is important to have the same outlet for the two transport technologies to enable a fair comparison.

The onshore pipeline routing from Le Havre to Rotterdam was performed considering the following methodology: follow existing pipeline routes, avoid nature reserves, minimize length, avoid densely populated areas, avoid geographic depressions and minimize height difference. This onshore corridor has been estimated to be 620 km long. The shipping corridor follows the existing shipping lanes for the

English Channel and the North Sea. This shipping corridor has been estimated to be 260 nautical miles long (480 km).

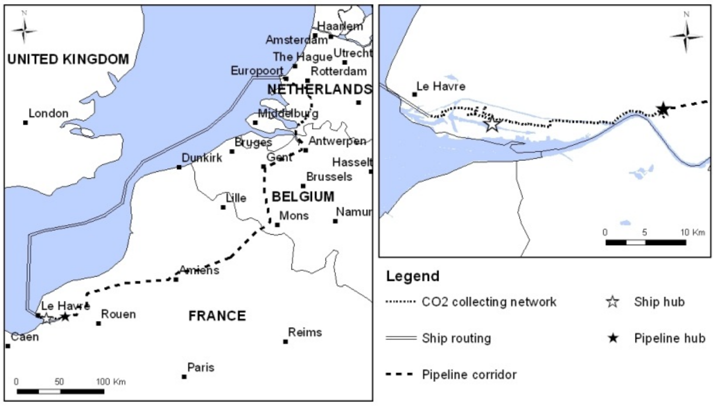


Figure 2. Pipeline onshore and ships corridors

2.1.2. Project characteristics

In order to perform a benchmark of the transport technologies, the costs assessments are performed for a base case scenario without any implementation strategy (no CO_2 profile difference over the project duration). Based on data collected from the industries in Le Havre on their CO_2 emissions, the profile of CO_2 transported is assumed to have the following characteristics:

1. A total annual capacity of 15.45 $MtCO_2$/y or 1813.7 tCO_2/h based on monthly peaks. It is worth noting that as the clusters peak flow do not all occur at the same time, the total annual capacity is lower than the sum of cluster daily peak flows.
2. An average annual flowrate going in the designed units of 13.1 $MtCO_2$/y or 1537.7 tCO_2/h (85 % of utilization rate). It is worth noting that the CO_2 flow is not constant within a year but follows a pattern.
3. Beginning of the operation: 2020
4. Project Duration: 30 years.

2.2. Technical options compared

For the two transport technologies compared, several options were designed to transport CO_2 from the clusters in Le Havre to Rotterdam. Indeed, the CO_2 transport and conditioning from the clusters to the hubs located in Le Havre can be done with different network configurations and conditioning locations. In addition, regarding the transport from Le Havre hubs to Rotterdam, several pipeline diameters and ship capacities can be used. The costs of those options are assessed. The designs and costs are detailed below for each transport chain.

2.2.1. Pipeline supply chain

As mentioned before, for the CO_2 transport from the clusters to the pipeline hub, two options are considered in order to reach the dense phase state and the pressure set at the export pipeline inlet (150 bar):

1. CO_2 is compressed to dense phase at the clusters level (110 bar) and reach the hub at a pressure above 80 bar. At the hub level, only a pump is required to reboost CO_2 up to 150 bar before the long distance transport.
2. CO_2 is sent to the hub in a gaseous form at a low pressure (9 bar) and is transformed in dense phase at the hub level.

The characteristics from the designs of the collecting network up to pipeline hub are shown in Table 1.

Table 1. Characteristics of the collecting network up to pipeline hub

Transport option	D_{MIN} ["]	D_{MAX} ["]	t_{MAX} (mm)	Power consumption [GWh/y]	Cooling water consumption [Mm^3/y]
Dense	6 5/8	20	17.1	1,257	166
Gaseous	16	68	11.9	1,767	220

Regarding the transport from Le Havre pipeline hub to Rotterdam, five diameters were tested for the 620 km long onshore pipeline. Due to the difference in pressure drops, these options have different numbers of pumping stations and energy consumptions as shown in Table 2. For all these options, CO_2 is delivered in Rotterdam at 200 bar and 25 °C.

Table 2. Export pipelines characteristics

D ["]	t [mm]	Number of pumping stations	Power consumption [GWh/y]
32	38.1	1	63
30	31.8	2	70
28	30.2	2	93
24	28.6	5	186

2.2.2. Shipping supply chain

For the transport from the clusters to the ship hub, three options are considered in order to transport and liquefy CO_2 to the conditions set at the hub (6.5 bar, -50.3 °C) before storing CO_2 onsite and loading on the ship:

1. CO_2 is sent from the clusters to a common liquefaction unit at the hub level in a gaseous form at low pressure (3 bar);
2. CO_2 is sent from the pooling clusters to a common liquefaction unit at the hub level in a gaseous form at a higher pressure (20 bar);
3. CO_2 is liquefied at the clusters level and then transported under liquid form by pipelines up to the hub (8 bar). Those pipelines are insulated.

The characteristics from the design of the collecting network up to ship hub are shown in Table 3.

Table 3. Characteristics of the collecting network up to ship hub

Transport option	D_{MIN} ["]	D_{MAX} ["]	t_{MAX} (mm)	Power consumption [GWh/y]	Cooling water consumption [Mm^3/y]
3bar	16	80	14.7	1,438	280
20bar	8 5/8	60	9.5	1,502	280
Liquid	8 5/8	36	6.4	1,397	283

Regarding the transport from Le Havre ship hub to Rotterdam, three ships' effective capacities are compared as shown in Table 4. These options lead to different fleets, cryogenic buffer storage capacities (in both harbours), investments and operating costs. For these three technical options, the average ship speed was set to 16.5 knots (Decarre et al., 2010) and the operating cycles include: mooring in Le Havre, loading, journey to Rotterdam, mooring in Rotterdam, unloading and return to Le Havre. It is assumed that the ships operate during the whole year and that maintenance is performed during off-peak periods. From vendor's consultation, the fuel consumption had been approximated to 36 kt of shipping fuel per year for the case of medium size ships. The fuel consumption of the two other cases are estimated using the Evans and Marlowe equation (Evans and Marlow, 1986).

In Rotterdam, CO_2 is unloaded to a buffer storage facility and reboosted to 200 bar and heated to 25 °C. It is assumed that there is no cost associated to the heating of CO_2 during the reconditioning in Rotterdam as frigories could be useful on a harbour.

Table 4. Ships characteristics

Name of the option	CO_2 carriers effective capacity [m^3/ship]	Number of ships	Utilization rate [%]	Buffer storage capacity [m^3]	Shipping fuel consumption [kt/y]
Small ships	21,825	5	72	90,000	39
Medium ships	30,555	3	86	110,000	36
Large ships	39,285	3	67	130,000	34

3. Cost evaluation methodology

3.1. Investment costs evaluation

In this paper, it is assumed costs applied to an "NOAK" (Nth Of A Kind) plant to be built sometime in the future when the technology is mature. Such estimates reflect the expected benefits of technological learning, but may or may not adequately account for the increased costs that typically occur in the early stages of commercialization (Metz et al., 2005).

Different investment costs estimation methods are used: a specific one for pipelines and a more common method for process units. In order to ensure consistency between the different methodologies, the investment costs evaluations are based on the material costs listed in Table 5. Investment costs are given in 2009 prices or reported using the CEPCI Index (Chemical Engineering, 2011). However in the cash flow profile, the investment costs are reported as an overnight cost assuming an equally shared investment over the construction time. For instance, process plants and ships are assumed to be built over three years (Schach et al., 2010) while 620 km long onshore pipelines are assumed to have a laying time of five years.

Table 5. Material prices list

Material	Costs [€/t]	Reference
Carbon steel	500	(MEPS (International) LTD, 2011)
Stainless steel	2,500	(MEPS (International) LTD, 2011)
Seamless carbon steel pipe	870	(Steel Business Briefing, 2011)
Ammonia	200	(French Finance Office, 2011)

3.1.1. Pipe methodology

A specific pipeline cost model for Europe and North America was developed by Geogreen© for the purpose of COCATE project. This model was not made public. In a nutshell, based on public pipeline data (Chandel et al., 2010; Heddle et al., 2003; International Energy Agency GreenHouse Gas R&D Program, 2005; McCoy, 2009; Parker, 2004; Serpa et al., 2011; Tarka and Wimer, 2010) the investment cost of CO_2 pipeline has been modelled as a function of its length, diameter, wall thickness[2] and a series of factors such as length factor or terrain factor. The onshore pipeline CAPEX falls into four parts: Material, Labour, Right-of-way (ROW) and Miscellaneous costs.

3.1.2. Factor methodology

A factor estimation method is used in order to estimate investment costs of process units where the estimated equipment costs are multiplied with direct[3] and indirect[4] cost factors to obtain the investment costs. Equipment costs and direct costs of carbon steel equipment are estimated using Aspen Process Economic Analyzer®, based on results from the process simulations under Hysys®. Equipment and Direct costs of components in carbon steel are adjusted, if necessary[5] (Romeo et al., 2008), to reflect the cost of applied stainless steel using a material factor of 1.3 (Eldrup, 2009). The investment cost for a given piece of equipment is then calculated by multiplying the specific component direct cost with the appropriate indirect cost factor (see Table 6). The total investment cost is then determined by summarizing the estimated investment cost for all components within defined system boundaries.

Table 6. Indirect cost factor as function of Direct cost (Eldrup, 2009)

Direct Cost lower limit [k€]	0	15	51	211	367	624	1,428	> 3,620
Direct Cost higher limit [k€]	15	51	211	367	624	1,428	3,620	
Indirect Cost Factor	2.23	1.86	1.71	1.65	1.63	1.59	1.58	1.50

However due to their specificity, two units of the transport supply chains are estimated differently: the pumps used in the pipeline export system and the reconditioning after shipping and the CO_2 carriers of the shipping export system. The equipment cost of pumps has been estimated to 1.5 M€/pump, from vendors contact, which lead to 3 M€/pump once direct and indirect costs are included. Regarding ships, their investment costs are evaluated directly using the ship's total investment cost per ship (Skagestad and Eldrup, 2009) which is a function of the effective capacity as shown in Table 7.

Table 7. Ship investment costs

Ship size	Total investment cost [M€/ship]
Small ships	40
Medium ships	47
Large ships	54

3.2. Operating and maintenance costs evaluation

The operating costs are split into fixed and variable operating costs.

3.2.1. Variable operating cost

The variable operating cost, being a function of the amount of CO_2 transported, covers consumption of electricity, steam, cooling water, ships' fuel and harbours fees. The annual variable operating costs are

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[2] A corrosion allowance should be taken into account in the pipeline design to account for the potential impact of impurities.

[3] Which includes erection, piping, secondary equipment, civil work, insulation, steel and concrete costs.

[4] Which includes engineering, administration, commissioning and contingencies costs

[5] A preliminary study has shown that CO_2 dehydration should be performed at 30 bar. Therefore, it is assumed that the material used is stainless steel until CO_2 pressure has reached 30 bar and in carbon steel afterwards.

estimated using the utilities consumptions given by technical designs, and utility and fees costs given in Table 8. These prices has been estimated for 2020, the beginning of the project, using 2020 forecast or 2011 prices and a yearly inflation of 2 % (European Union average inflation between 2000 and 2010 (Trading Economics, 2011)).

It is assumed here that steam can be extracted from industries in Le Havre. This steam is considered to be available at 5 bar and 150 °C (inlet condition of a low pressure turbine (Shelton and Lyons, 2000)) and has an efficiency of 23 % (Göttlichter, 2004) to produce electricity and therefore an implicit cost of 4.2€/GJ (23 %×66 €/MWh).

As the North Sea is a Sulphur Emission Controlled Area, it is likely that from 2020 and over the duration of the project, ships will have to run on low sulphur fuel (International Maritime Organization, 2009; Matthias et al., 2010). Therefore the fuel used by the ships is assumed to be distillate fuels. The harbour fees in the case of shipping transport had been estimated from Le Havre Development Agency and Port of Rotterdam NV consultations.

Table 8. Utilities costs and fees list

Utility/Fee	Cost	Reference
Electricity (France) [€/MWh]	66	(The Europe's Energy Portal, 2011)
Electricity (Netherland) [€/MWh]	120	(The Europe's Energy Portal, 2011)
Steam (France) [€/m^3]	4.2	
Cooling water [€/m^3]	0.02	(Haugen et al., 2009)
Ships' fuel [€/t]	790	(US Energy Information Administration, 2010)
Habours fees for both Le Havre and Rotterdam [€/t_{CO2}]	2	

3.2.2. Fixed operating cost

The fixed operating cost depends on the investment cost and covers maintenance, insurance, and labour costs. The annual fixed operating cost is set to 5 % of investment costs for process units (Chauvel, 2003). Regarding pipelines, it is also assumed to be a percentage of the pipeline investment costs. However we made this percentage varying with the diameter: as shown in Table 9, the smaller the diameter, the higher the percentage of the investment granted. Those percentages were set considering in-house and publicly available data (Chandel et al., 2010; Heddle et al., 2003; International Energy Agency GreenHouse Gas R&D Program, 2005; McCoy, 2009; Tarka and Wimer, 2010) as shown in Table 9. Concerning ships, the annual fixed operating cost per ship is a constant function of the ship size (Drewry, 2009) as presented in Table 10.

Tables 9. Pipelines fixed operating cost

Diameter range ["]	Percentage of pipeline investment
<10	5
10≤ < 26	3
≥ 26	1

Tables 10. Ships fixed operating cost

Ships size	Annual ship fixed operating cost [M€/y/ship]
Small ships	2.0
Medium ships	2.3
Large ships	2.4

3.3. Key Performance indicators (KPIs)

As the amount of CO_2 transported is the same for all the studied cases, the Net Present Value of project costs (NPV) is used as the key indicator to compare the cost of the different technologies. The NPV is equal to the sum of discounted costs flow during the project duration as no revenue is considered. The

NPVs are estimated in 2020 (assumed beginning year of operation) assuming a real discount rate of 8 %[6] and a duration of 30 years.

However in order to approximate the average discounted carbon credit per tonne transported over the project duration that would be required as income to match the net present value of capital and operating costs for the project, the CO_2 Transport Threshold Cost [€/t] is estimated for the two global transport chains. The CO_2 Transport Threshold Cost is equal to the annual costs divided by the annual amount of CO_2 transported (equal to captured).

$$\mathrm{CO_2\ Transport\ Threshold\ Cost} = \frac{\mathrm{Annual\ OPEX + Annualized\ investment}}{\mathrm{Annual\ CO_2\ transported}}$$

4. Results and discussions

4.1. Pipeline transport chain

4.1.1. CO_2 collecting network up to pipeline hub

The comparison of the two collecting networks options up to the pipeline hub shows clearly that the dense phase transport is the most economical options as it leads to a net present value of costs 30 % lower than the gaseous option (see Figure 3). In the case of CO_2 transported in the gaseous form, it is not only the pipeline investment that is more important but also the energy requirement. It is worth nothing that even if the decentralization of compression in the dense phase transport increases the compression investment costs, it is still lower than in the case of gaseous transport.

Therefore if there is enough space and water available at the clusters level, the CO_2 should be conditioned in dense phase from the beginning. This result is specific to this kind of configuration (40 km long collecting network). For smaller collecting networks, one should keep in mind the option of transporting CO_2 in the gaseous phase. However for Le Havre configuration, it might also be better to allow a smaller pressure drop inside pipelines to avoid having to do the first stages of CO_2 compression twice at different levels as they are the most energy intensive and the most expensive stages.

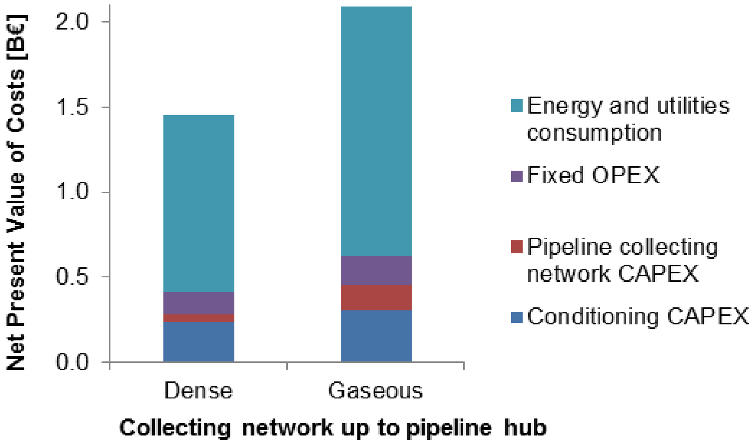

Figure 3. Costs of pipeline collecting networks options

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[6] This real discount rate of 8 % corresponds to a nominal discount rate around 10 % if an inflation rate of 2 % is considered.

4.1.2. Onshore pipeline export system

The results of the export pipeline costs assessment are presented in Figure 4. It appears that the best options are the 28" and 24" pipelines which are equivalent options in terms of net present values. The 24” pipeline option limits the investment upfront, but requires five pumping stations instead of two for the 28” pipeline. Even with sensitivity analyses on electricity price, project duration, steel price and discount rate, there is no obvious choice between the 24” and 28” pipelines as shown in Table 11. However, here the low electricity price in France provides an advantage for the small diameters with higher number of pumping stations and higher electricity consumption.

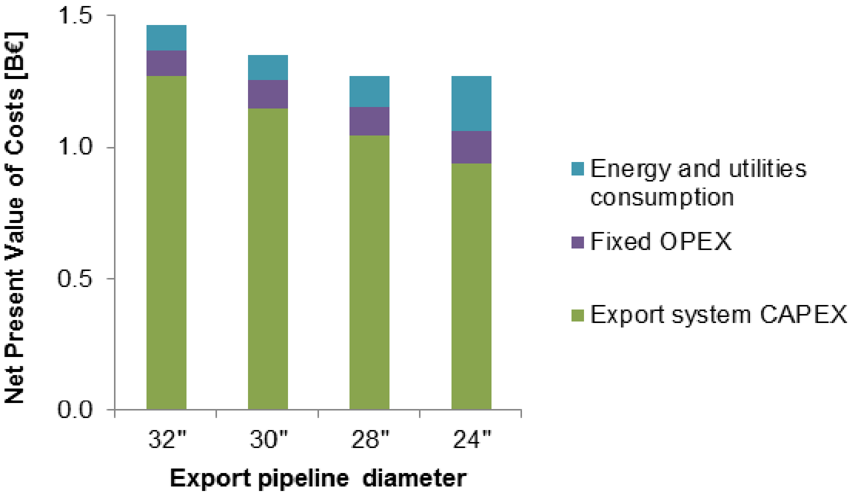

Figure 4. Costs of pipeline diameters options

Table 11. Sensitivity analysis of the NPV of the 24" compared to 28" pipeline depending different parameters

Discount rate [%]	Project duration [y]	Electricity price variation [%]	Steel price variation [%]	NPV of the 24" compared to 28" [%]
8	40	0	0	0.2
8	30	50	0	3.1
8	30	-50	0	-4.2
4	30	0	0	4.7
8	30	0	25	1.6
8	30	0	-25	1.3
8	30	0	-25	1.3

4.2. Shipping transport chain

4.2.1. CO_2 collecting network hub to ship hub

Even if net present values are similar for all collecting networks (gaseous 3 bar, gaseous 20 bar and liquefied) as costs are mainly driven by the energy and the cooling water consumptions (see Figure 5), the cost estimation shows that the liquefied transport option is the cheapest. The differences between the options are mainly due to investment costs of pipelines. Indeed, the denser the CO_2 is transported, the smaller are pipeline investment costs due to the reduction of the pipeline diameter and to the material used (carbon steel vs. stainless steel). Even if liquefied transport inside the network leads to more decentralized units at the cluster level and to insulation requirements, the induced increase in costs is small compared to the decrease of the pipeline costs, as in other cases, several liquefaction units are required in parallel to cope with the volume to be liquefied.

Thus, the liquefied transport system to the ship hub is the cost-optimized solution. It is however important to emphasize that considerations regarding space, access to cooling water and treatment of ammonia could place site specific restrictions. Indeed, the liquid transport system reduces the size of the transport infrastructure which can be an important factor on industrial sites with limited free space. However this option requires more space and access to cooling water at the clusters level.

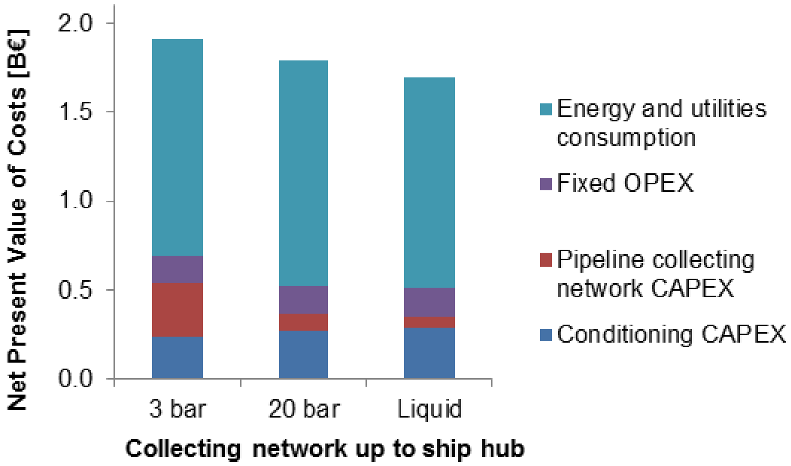

Figure 5. Costs of shipping collecting networks options

4.2.2. Shipping export system

The cost estimations indicated that the different ship capacities studied led to very similar results in terms of costs as shown in Figure 6. As the medium size ships have a higher utilization rate, as shown in Table 4, and therefore a lower investment costs for the amount of CO_2 transported, the medium ship alternative is the best option for the transported volumes considered. However it might not be the best option for other flow patterns and it is likely that the best option would be the fleet which maximizes the capacity utilization rate, by for example combining ship sizes.

The estimation of the harbour fees is based on the fact that, today, CO_2 is considered a chemical product. If it had not been considered as a valuable product, one of the harbour fees could have been removed leading to a total discounted cost reduced by 170 M€.

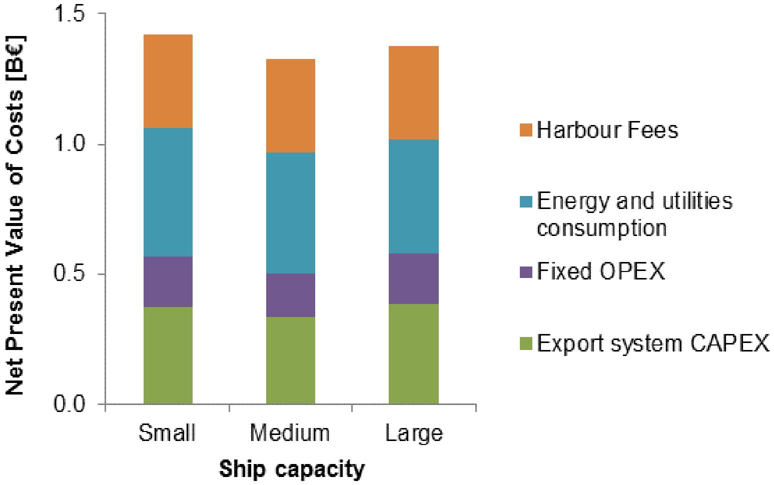

Figure 6. Costs of ship capacities options

4.1. Comparison of transport technologies

In this section the global NPV of the pipeline and shipping optimal supply chains to transport CO_2 are compared. Prior to the CO_2 collecting network and after the reconditioning in Rotterdam, CO_2 characteristics are the same for both transport systems. Hence comparisons and sensitivity analyses are performed on the transport from clusters in Le Havre (i.e. after capture) to Rotterdam after reconditioning.

4.1.1. Results

Figure 7 sums up the costs of the two transport systems from clusters to Rotterdam. For the considered flow (13.1 $MtCO_2$/y transported from 2020) and under the assumptions stated previously, the cost-optimized option from Le Havre to Rotterdam is the transport by an onshore pipeline, which is 10 % cheaper than shipping (17.1 €/t for the pipeline versus 18.9 €/t for the shipping). However, if CO_2 was not considered as a valuable product, the cost for the shipping supply chain would had been lowered by 1 €/t and the two technologies would be almost comparable for the transport of CO_2 from Le Havre to Rotterdam.

Even though the costs of the different systems seem to be close, the cost breakdowns of the two transport systems differ as shown in Figure 7. The investment costs are higher for the pipeline transport while the operating costs are higher for shipping. Indeed, the money invested in 2020 (beginning of the transport) for the pipeline supply chain is 50 % higher than in the case of shipping. As a consequence the two technologies will be impacted differently by changes in the project characteristics such as the discount rate, the project duration and the energy prices. It is worth noting that, for both transport technologies, the specific costs due to the combination of multiple CO_2 sources represent 5 % of the overall transport costs. This value emphasizes the interest of transporting CO_2 from a group of various size industries.

However others factors than costs must also be included in the technology decisions. The two technologies have different pros and cons. For example, a pipeline supply system is not flexible, involves high investment costs, has routine constraints and can lead to social acceptance issues. However, pipelines have the advantage of being insensitive to weather, of being a continuous process with automation possibilities. Regarding the shipping supply system, the technology is less advanced (unloading...), presents collision risks (Ha-Duong and Loisel, 2011), has higher operating costs, is more sensitive to weather/traffic conditions and leads to higher direct emissions. However shipping is flexible, less capital intensive, requires lower construction time and presents the possibility of co-utilization as CO_2/LPG ships (Aspelund et al., 2009).

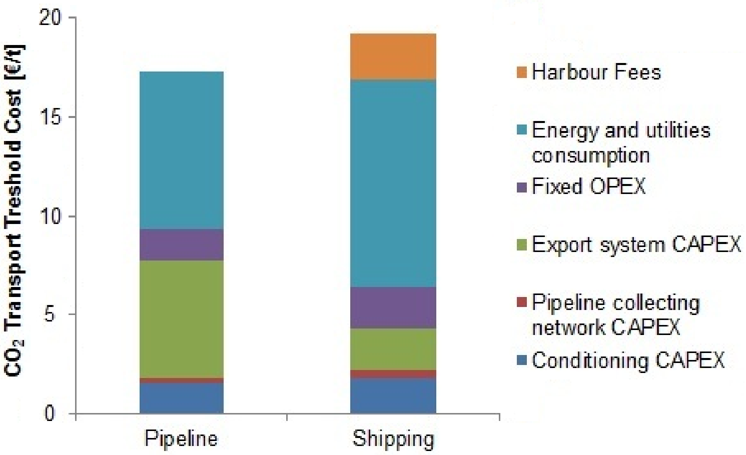

Figure 7. Costs of pipeline and shipping supply chains

4.1.2. Comparison with the literature

In this section, the costs obtained for ship and pipeline are compared to the most recently published report on transport costs, the ZEP report (European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2011). In order to compare the pipeline and shipping costs with the ZEP report, COCATE costs should not include the conditioning and should be adjusted to a full utilization over 40 years as summed up in Table 12.

This leads to pipeline costs which are 30 % higher for COCATE than the ones calculated by the ZEP. This is due to the fact that COCATE considers a specific corridor routing with obstacles crossing while the ZEP report considers a flat topography with no obstacle crossing.

The comparison of the shipping chain costs obtained in COCATE with the cost of transport estimated by the ZEP shows that the COCATE costs, for a utilization rate of 100 % over 40 years of operation, is around 20 % higher than ZEP estimations. The differences come from the assumptions. In COCATE, ships are assumed to run on low sulphur fuel, such as distillate fuels, while in the ZEP report the use of marine diesel oil is suggested. Moreover the reconditioning pressure after shipping is higher in COCATE (200 bar) than in the ZEP report (60 bar). Harbour fees in COCATE were calculated with data specific to Le Havre Harbour and Port of Rotterdam and which may be more expensive than the ones taken into account in the ZEP report.

The costs presented in this paper are then in the range of the costs obtained in the ZEP report and the differences can be explained by the specificity of the case studied. However it is worth noting that due to the reasons stated previously, specific cases might be more expensive than the costs suggested in the ZEP report.

Table 12. Comparison of CO_2 Transport Threshold Costs between COCATE project and ZEP

	COCATE Project		Based on ZEP Report			
Capacity [Mt/y]	15.45	15.45	2.5	10	15.45[4]	20
Utilization rate [%]	85	100	100	100	100	100
Duration [y]	30	40	40	40	40	40
Pipeline without conditioning [€/t]	7.9	6.9	X	6.9	5.4	4.2
Shipping without conditioning [€/t]	8.3	7.8	9.5	X	6.6	5.7

4.1.3. Sensitivity analyses

Sensitivity analyses were performed on the discount rate, the project duration and the energy prices for the cost-optimized solution for shipping and pipeline as shown in Figure 8. As the quantities of CO_2 transported are not constant when the sensitivity analysis is performed on the project duration, the NPV cannot be used as a key performance indicator to perform the sensitivity analysis (Babusiaux and Pierru, 2002). The key performance indicator used in this section is therefore the CO_2 Transport Threshold Cost.

The discount rate represents the present value of future money. This value is specific to the type of investor. For example, the State uses lower discount rate than average companies while Oil & Gas companies and companies dealing with risk use a higher discount rate. Therefore it is important to run a sensitivity analysis to discount rate and see the impact on the CO_2 Transport Threshold Cost as the CAPEX annuity is reduced when the discount rate decreases. Since the total amount of CO_2 transported and OPEX are constant throughout the project duration, the discount rate only impacts the CAPEX annuity. When increasing the discount rate, the more important the infrastructure investment is, the more the CAPEX annuity will weigh on the threshold cost. Thus, when increasing the discount rate, ship transport becomes less expensive than the pipeline.

The lifetime of the infrastructure is different for shipping and pipeline. The pipeline can be used for at least 40 years while a ship can be chartered for maximum 30 years and should be reinvested if the project duration is extended. Moreover as the cost structures (CAPEX/OPEX) of the two export systems are not the same, the optimal technology can change if the project duration is changed. The sensitivity analysis shows that the CO_2 Transport Threshold Cost is rather insensitive to an increase or decrease of the duration of 10 years for ship transport. For CO_2 transport by pipeline, the threshold cost is rather insensitive to a duration increase but more sensitive to a duration decrease. Indeed, the only part of the CO_2 Captured Threshold Cost which depends on the project duration is the CAPEX annuity. As the pipeline is much more capital intensive than ships which are a liquid asset, the effect of the project duration on the threshold cost is more obvious.

The future prices of energy represent an important uncertainty for the costs and the shares of energy costs are not the same in the two transport systems. Therefore it is important to perform a sensitivity analysis on energy prices. As shipping transport does not consume only electricity but also shipping fuel, the sensitivity is performed on the energy (electricity and shipping fuel) prices, and shows that the energy prices are a key factor for CO_2 transport costs. When increasing (decreasing) the electricity cost by 50 %, pipeline and shipping costs both increase (decrease) by 20 %. Regarding the shipping fuel, it was assumed that ships will run on low sulphur fuel. However, if they run with today's fuel, the marine diesel oil (European Technology Platform for Zero Emission Fossil Fuel Power Plants, 2011), the fuel cost is more than halved. This cost decrease in the shipping transport option makes it more competitive to the pipeline supply chain. Both transport options are very sensitive to the energy prices as here, the conditioning before transport is included. If those energy prices were to decrease, the shipping option would become almost competitive with the pipeline option.

As shown in Figure 8, the sensitivity analysis shows that energy prices is the factor influencing costs the most, then comes the discount rate and finally the project duration. As pipeline is much more capital intensive than shipping, it is much more sensitive to discount rate and project duration compared to shipping. However, onshore pipeline is almost always the best choice to transport CO_2 from Le Havre to Rotterdam under the assumptions described in this paper and for the scenario studied: a one-step implementation strategy in Le Havre.

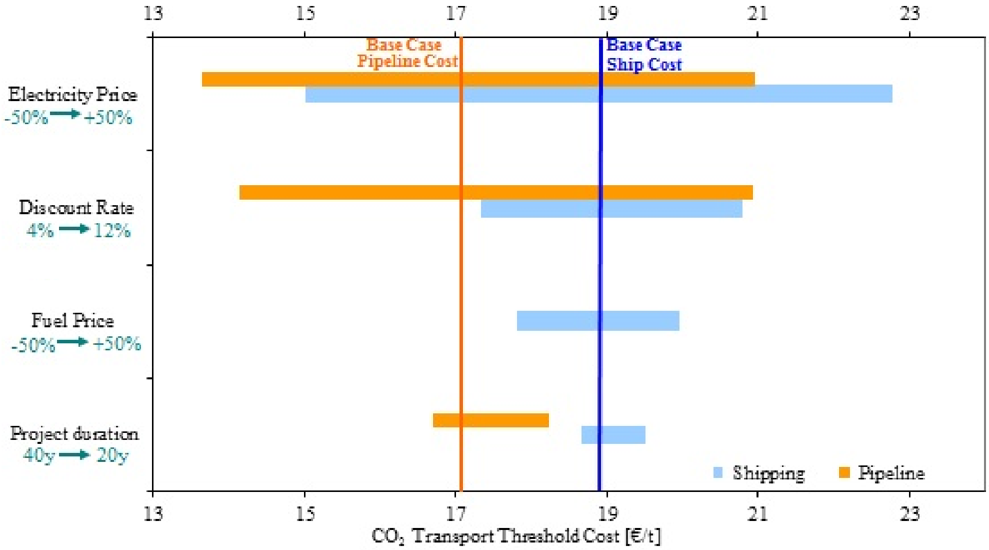

Figure 8. Summary of the sensitivity analysis

5. Conclusion

This paper compares the costs of two technologies to transport CO_2 from a group of various size industries from Le Havre (France) to Rotterdam (Netherlands). The costs of transporting a total of 13.1MtCO_2/y from small- to large-scale emitters around Le Havre (France), to Rotterdam (Netherlands) via onshore pipeline or shipping are evaluated.

Sources send emissions to five CO_2 capture centres, which are then linked via a 40 km long collection network to deliver the treated CO_2 to the point of export. This network was designed to accommodate daily peak flow rates and five collection network designs (gaseous and dense for the CO_2 collection network up to the pipeline hub, 3 bar, 20 bar and liquid for the CO_2 collection network up to the ship hub) were considered for the various export scenarios evaluated in the study. The economic evaluation established that conditioning CO_2 at the cluster level, rather than at point of export, and transporting it in dense phase was the most cost-effective solution for both export systems. For the CO_2 pooling network up to pipeline export, dense transport is 30 % cheaper than in the case in which CO_2 is transported gaseous. Before shipping export, the cost evaluation shows that the most cost-efficient option is to liquefy CO_2 at the cluster level. Not only does it decrease the costs, it also reduces the network size which can be an important factor on industrial sites with limited available space. However this solution requires both more space and access to cooling water at the clusters level as the liquefaction is decentralized.

As for exporting the CO_2 from Le Havre to Rotterdam, the evaluation highlighted three potential transport solutions: either onshore via one 24” or one 28” diameter pipeline or offshore using three ships with effective capacities of 30,000 m^3 each. For the 620 km long onshore pipeline, the 28" and 24" diameter pipelines are equivalent options in terms of costs and even the sensitivity analyses do not lead to a more obvious choice. The 24” pipeline option limits the investment upfront but requires five pumping stations instead of two for the 28” pipeline. For the 260 nautical miles shipping transport, costs estimations show that different ship size options lead to similar costs. However as the utilization rate is higher for the medium size ship, its cost is slightly lower.

The benchmarking performed shows that, considering the assumptions taken for COCATE project, the most cost-efficient technology to transport the CO_2 from Le Havre to Rotterdam is one onshore pipeline (10 % cheaper than shipping).

Sensitivity analyses show that the factor influencing the most the costs is energy prices, and then comes the discount rate and finally the project duration. Under the assumptions in this project, sensitivity analyses confirm that onshore pipeline is mostly the best choice to transport CO_2 from Le Havre to Rotterdam.

However the present paper does not take into account any implementation strategy. It is likely that if CCS starts, large CCS infrastructures would be deployed step by step. In these cases, CO_2 shipping could be used in a first time while pipelines networks would be deployed later on. This deployment strategy is interesting in order to limit initial investments and risks due to uncertainties regarding the future CO_2 volume transported.

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