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Multi-criteria analysis of two CO_2 transport technologies

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Abstract

This paper illustrates a methodology for multi-criteria analysis of CCS chains by comparing two transports technologies for a case study in which 10 Mt/y of CO_2 from an industrial cluster are transported over 500 km by onshore pipeline and CO_2 shipping. This case study compares not only project costs but also other criteria such as the greenhouse gas emissions, the energies and cooling water consumptions, etc. The multi-criteria analysis of the two cases shows that the pipeline technology exhibits the best key performance indicators except regarding the initial investment. Indeed the pipeline transport is less expensive, consumes much less utilities (fuel, water and electricity) and is less climate intensive than the shipping transport. The shipping transport required however lower upfront investments for similar overall project costs. A consequence of this might be that even if the pipeline transport has most of the best criteria, shipping might be used during the first CCS chains deployment in order to limit investment upfront, and therefore financial risk, while pipeline transport will be used in a well established CO_2 market.

Keywords: Carbon Capture and Storage (CCS); Multi-criteria analysis; Transport; Pipeline; Shipping.

1. Introduction

Carbon Capture and Storage (CCS) is considered to be one of the most promising alternatives for reducing anthropogenic greenhouse gas (GHG) emissions [1]. To bring CCS closer to commercial realization, the viability of CCS value chains must be explored. For a commercial CCS chain to be successful, it must be sustainable and therefore take into account the three pillars of sustainability: profitability, planet and people. To ensure the critical evaluation of the viability of a CCS chain with respect to multiple criteria, a consistent and transparent methodology was developed and published [2].

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The value of such a methodology is in the support it provides to decision makers to select the best alternatives for the CCS chains.

Several papers and reports [3-5] had published comparisons of pipeline and shipping CO_2 transport cases based on costs. However, in several of these comparisons, the costs evaluation lead to similar costs estimates between the systems while authors identify other criteria which can play a significant role for investments decision. In this work, we focus in particular on systematic multi-criteria assessment of CCS transport options. In order to illustrate the methodology a case study, benchmarking two transports technologies, is performed. In this case study, onshore pipeline and CO_2 shipping between two onshore harbours are compared including not only the economic aspects but also the GHG emissions, the energies and the cooling water consumptions.

2. Methodology

2.1. System boundaries and design

The case study, presented here, is based on a scenario described by The Zero Emission Platform [4] in which 10 M tCO_2/y of CO_2 from an industrial cluster are transported over a distance of 500 km. The assessments include mass and energy flows, capital investments (CAPEX), operating expenses (OPEX) and GHG emissions from the point where purified CO_2 is delivered to capture until after the CO_2 regeneration by stripping. The conditioning parts of the two transport chains are simulated under Aspen Hysys® while the export systems designs had been performed based on correlations from the literature [3] in order to obtain their utilities consumptions and components characteristics. Based on these system simulations, equipments and flows characteristics as well as utilities consumptions are obtained for both pipeline and the shipping transport chains, providing important inputs for the techno-economic and environmental assessments.

2.1.1. Case characteristics

The CO_2 emission profile from the cluster is assumed to lead to the following infrastructure characteristics:

- A total annual capacity of 10 $MtCO_2$/y or 1,142 tCO_2/h;
- An average annual flowrate of 10 $MtCO_2$/y (100 % of utilization rate). The emission profile is assumed to be constant over a year;
- Project duration: 30 years.

2.1.2. Pipeline transport system

At the inlet of an onshore pipeline, dense CO_2 at 150 bar and ambient temperature is required [6] while CO_2 is delivered at 1 atm and 25 °C from CO_2 capture [7]. The conditioning before pipeline transport is therefore needed, and consists of four compression stages and pumping, combined with the removal of unwanted components (dehydration)[†]. In order to assess the characteristics of the conditioning, simulations are performed under Aspen Hysys®. A pressure ratio close to 3 is considered for each compression stage while compressors and pump efficiencies are assumed to be respectively 90% and 75%. In between the compression stages, cooling to 25 °C and removal of the water content are performed.

At the outlet of the onshore pipeline, CO_2 is delivered, after reconditioning, at 200 bar which correspond to the inlet pressure of an offshore pipeline [3]. Depending on the diameter, the onshore

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[†] The TEG (triethylene glycol) dehydration unit is not included in the assessment.

pipeline chain will have different characteristics: pressure drop, number pumps, energy consumption, costs, etc. Here four pipeline diameters from 18" to 24" are considered, and the costs comparison, not presented here, highlighted the 22" option as the most cost-efficient one. The 22" pipeline is therefore the only pipeline option presented in this paper. In order to take into account the over length of a pipeline (due to tee, the terrain, etc.), the pipeline length is assumed to be 10% superior to the transport distance. The pipeline designs are performed based on the minimal thickness required [8] and according to the API specification 5L standard. The pressure drop is calculated using the Fanning equation considering no elevation effect while the power associated with the pipeline pumping is obtained using Aspen HYSYS®. The number of pumps is estimated assuming that the pressure in the pipeline shall not fall under 90 bar (i.e. stay above the critical pressure) and a capacity of 2 $MtCO_2$/y per pump.

Table 1. Technical assessment of the pipeline transport options

D ["]	t [mm]	Number of pumps	Cooling water consumption [Mm^3/y]	Conditioning	Export system
22	15.9	15	25	865	165

2.1.3. Shipping transport system

At the inlet of a shipping export, liquid CO_2 at 6.5 bar and -50 °C is required [3] while CO_2 is delivered at 1 atm and 25 °C from CO_2 capture. Conditioning before pipeline transport is therefore needed, and consists of three compression stages and followed by a liquefaction process using ammonia cooling cycles and expansion [9], combined with the removal of unwanted components (dehydration)[‡]. In order to assess the characteristics of the conditioning, simulations are performed under Aspen Hysys®. A pressure ratio close to 3 is considered for each compression stage while compressors and pump efficiencies are assumed to be respectively 90% and 75%. In between the compression stages, cooling to 25 °C and removal of the water content are performed.

At the outlet of a shipping chain, dense CO_2 is delivered, after reconditioning, at 200 bar which correspond to the inlet pressure of an offshore pipeline [3]. Depending on the ships size, the shipping chain will have different characteristics: number of ships in the fleet, buffer storages capacity, fuel and electricity consumption, costs, etc. Here three ship sizes are considered: 21,825 m^3, 30,555 m^3, 39,285m^3 [3]; and the costs comparison, not presented here, pointed out the 21,825 m^3 option as the most cost-efficient one. The 21,825 m^3 CO_2 carriers is therefore the only shipping option presented in this paper. After the liquefaction and before the reconditioning, cryogenic buffer storages are required as shipping is a lead to steps export while the liquefaction and the injection are continuous processes. It is here considered that volume of each of these buffer storages is equal a ship volume [4]. The duration of a shipping transport cycle is assumed to be 62.5 h per cycle [4][§] while ships are considered to operate over 350 days per year[**]. The ship fuel consumption is assumed to be proportional to the distance and transport volume and estimated based on Roussanaly et .al figures [3]. The reconditioning of CO_2 after shipping consists of repumping until 200 bar followed by heating to atmospheric temperature. As the frigories have an economic value on an industrial site, the investment and operating costs of the heating during reconditioning are not considered here. The number of pumps is estimated assuming a capacity of 2 $MtCO_2$/y per pump while the associated power is obtained using Aspen HYSYS®.

[‡] The TEG (triethylene glycol) dehydration unit is not included in the assessment.

[§] Considering a Mooring/Loading/Departure and Mooring/Unloading/Departure durations of 12 h each and a shipping speed of 14 knots (25.9 km/h).

[**] 360 h (15 days) per year are used for maintenance.

Table 2. Technical assessment of the shipping transport options

Shipping option	Ship capacity [m^3/ship]	Number of ships	Buffer storage [m^3]	Cooling water [Mm^3/y]	Conditioning electricity [GWh/y]	Reconditioning electricity [GWh/y]	Fuel [kt/y]
Small ships	21,825	3	43,650	199	1,060	62	31,011

2.2. Costs evaluation

2.2.1. Investment costs evaluation

This paper assumes costs which apply 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.

Different investment costs estimation methods are used: a specific one for pipelines and a more common method for process units. Investment costs are given in 2009 prices or reported using the CEPCI Index. 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 while the onshore pipeline is assumed to have a laying time of five years [3].

2.2.1.1. Pipeline methodology

The pipeline investment costs are determined assumed a CAPEX for onshore pipeline of 47,380 $€_{2009}$/"/km [10]. This cost is based on maximum operating pressures of 150 bars for onshore transport in a North European context.

2.2.1.2. 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[††] and indirect[‡‡] cost factors to obtain the investment costs in a European context. 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, to reflect the cost of applied stainless steel using a material factor of 1.3 [11]. 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 3). The total investment cost is then determined by summarizing the estimated investment cost for all components within defined system boundaries.

Table 3. Indirect Cost factor as function of Direct Cost [11]

Total Direct Cost lower limit (k€)	0	15	51	211	367	624	1,428	> 3,620
Total 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

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

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

shipping export system. The equipment cost of pumps has been estimated to 0.8 M€/pump, from vendors contact, which lead to 1.7 M€/pump once direct and indirect costs are included. Regarding ships, their investment costs are evaluated directly using the ship total investment cost per ship [3] which is a function of the effective capacity.

2.2.2. Operating and maintenance costs evaluation

The operating costs are split into fixed and variable operating costs. 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 estimated using the utilities consumptions given by technical designs, and utility costs and fees given in Table 4. The fixed operating cost depends on the investment cost and covers maintenance, insurance, and labour costs. The annual fixed operating cost is set to 6 % of investment costs for process units. Regarding pipelines, it assumed to be 6,630 €/km/y [10]. Concerning ships, the annual fixed operating cost per ship is a constant function of the ship size [3].

Table 4. Utilities costs and harbour fees

Utilities	Costs	Units
Electricity	55.5	€/MWh
Cooling water	0.025	€/m^3
Fuel cost	370	€/t_{fuel}
Harbour fees	2	€/t_{CO2}

2.3. GHG emissions

The GHG emissions caused by the transport systems, and their associated energy, materials and services are assessed by a hybrid-Life Cycle Assessment (LCA) approach. Hybrid-LCA combines physical processes data with economic data, this combination enables to cover emissions that will typically be lost when only physical process data is used. In addition as it uses techno-economic results, it also ensures the consistency of the GHG assessment with the techno-economic assessment.

GHG emissions from physical and energy flows data is modelled with inventory data from Ecoinvent 2.3 (Table 5) [12], while the GHG emissions from OPEX and CAPEX, in monetary units, is modelled with data from the Carnegie Melon University Economic Input-Output life cycle Assessment method (EIO-LCA Method) [13][§§] (Table 6).

The different GHG emissions are calculated into CO_2 equivalents (CO_2e) according to the guidelines given by IPCC [14] and summarized. This sum indicates the potential climate effect and is often referred to as the global warming potential (GWP).

Table 5. Overview of Ecoinvent process used to model the physical flows [12]

OPEX/CAPEX	GWP factor	Unit
Carbon Steel at factory	1.45	kg CO_2e / kg steel
Drawing of steel pipes	0.43	kg CO_2e / kg steel
Electricity, medium voltage at grid, European mix	0.50	kg CO_2e / kWh
Heavy fuel oil, at regional storage/RER U	0.45	kg CO2e / kg oil
Burning of heavy fuel oil in tanker	3.11	kg CO2e / kg oil

[§§] The IO data is for the American economy in 2002 and to convert it into 2009 equivalents in euros a conversion factor of 0.74 EUR_{2009}/USD_{2002} is used for capital investments and 0.92 EUR_{2009}/USD_{2002} for operating expenses.

Table 6. Overview of entries in the EIO-LCA Method used to model the monetary flows [13]

OPEX/CAPEX	GWP factor	Unit
Pump and pumping equipment manufacturing	0.56	kg CO_2e / $\$_{2002}$
Non-residential maintenance and repair	0.62	kg CO_2e / $\$_{2002}$
Non-residential manufacturing structures	0.44	kg CO_2e / $\$_{2002}$
Air and gas compressor manufacturing	0.56	kg CO_2e / $\$_{2002}$
Ship building and repairing	0.73	kg CO_2e / $\$_{2002}$
Scenic and sightseeing transportation and support activities for transportation	0.50	kg CO_2e / $\$_{2002}$

2.4. Multi-criteria Key Performance Indicators (KPIs)

Seven Key Performance Indicators (KPIs) are considered to benchmark the two technologies:

- The Net Present Value (NPV) of costs: equal to the total discounted costs of the technology over the project duration;
- The GHG emissions: equal to the total discounted amount of CO_2e emissions due to investment and operating costs;
- The CO_2 Avoided transport cost: equal to the annual costs of the transport chain, including the investment costs annuity, divided by the annualized amount of CO_2 avoided by the transport (equal to the amount transported minus the GHG emissions) as shown in the equation (1). This KPI, linking the techno-economic and environmental aspects, approximate the average discounted carbon credit per tonne avoided over the project duration that would be required as income to match the net present value of transport costs.

$$\text{CO}_2\text{ Avoided Transport Cost} = \frac{\text{Annual OPEX} + \text{Annualized investment}}{\text{Annualized CO}_2\text{ avoided}} \quad (1)$$

- Initial investment amount: highlight the financial risk of a technology. Indeed, the more a technology requires investment upfront, the more it is risky on a financial point of view.
- Cooling water consumption: can be a critical factor in the decision of the transport technology. Indeed conditioning requires large amount of water which can be an issue depending of the location.
- Electricity consumption: which is a critical factor as the more electricity intensive is a technology the most it will be sensitive to electricity cost variations.
- Fuel consumption: is a critical factor to ensure a consistent comparison between the two technologies, as only shipping consumes maritime fuel.

For the two technologies compared in this study, these indicators will be pictured in a spider diagram. In this system, the highest value of the two technologies KPI is set to the border and the more a KPI is ranked close to the border, the less the technology is attractive. Therefore the theoretical and ideal technology, i.e. with no impact, would be pictured as a dot located at the centre of the chart.

3. Results and discussions

For the considered flow and under the technical and costs evaluation assumptions stated previously, the two transport technologies have very similar costs. With a Net Present Value of costs of 1.7 B€, the onshore pipeline is only 9% less expensive than the shipping option (1.8 B€). Therefore the optimal technology for the case cannot be selected only considering the overall project costs but shall be tempered with a multi-criteria assessment.

The results of the different criteria assessments are presented in Fig. 1 for the two cost-optimized transport technologies for the considered flow profile and under the assumptions stated previously. The multi-criteria analysis shows that the pipeline technology exhibits the best KPIs except regarding the initial investment. However there are different discrepancies between the different technologies among the different KPIs. Indeed, even if the are only small differences between the costs of the two cost-optimized options, the pipeline transport consumes much less utilities (fuel, electricity and water) and is less climate intensive than the shipping transport. In addition, even if, the two options have similar overall costs, their costs breakdowns are different. Indeed, the onshore pipeline chain requires more than twice the upfront investment of the shipping option while the shipping chain leads to higher operating costs. The shipping transport required lower upfront investments for almost the same overall project costs. A consequence of this might be that even if the pipeline transport has most of the best criteria, shipping might be used during the first CCS chains deployment in order to limit investments upfront, and therefore financial risk, while pipeline transport will be used in a well established CO_2 market.

It is worth noting that other parameters, than the ones included here, can also be relevant when comparing two transport technologies. The choice of parameters will be depend on the case characteristics (location, context, perspective). For example, pipelines have the advantage of being insensitive to weather, of being a continuous process with automation possibilities, etc.

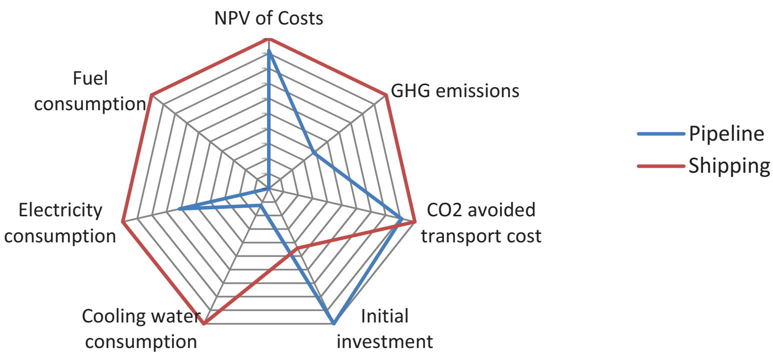

Fig. 1. Multi-criteria analysis of the pipeline and shipping transport chains

4. Conclusions

This paper presents a methodology for multi-criteria benchmarking of CCS chains and illustrates it on the benchmark of two transports technologies. In this case study, in which 10 Mt/y of CO_2 from an industrial cluster are transported over 500 km, onshore pipeline and CO_2 shipping are compared including not only the project costs but also the GHG emissions, the electricity and the cooling water consumption, etc. The multi-criteria analysis emphases the interest in the pipeline technology for CO_2 transport as it exhibits the best results (costs, GHG emissions, fuel, water…) except regarding the initial investment. However, due to financial risks, shipping might be used during the first CCS chains deployment in order to limit investments upfront while pipeline transport will be used in a well established CO_2 market.

To ensure a critical evaluation of the viability of a CCS chain, consistent and transparent multi-criteria analysis, as presented here, shall be performed. The value of such a methodology is in the support it provides to decision makers to select the best alternatives, bring CCS closer to realisation and enabling the development of CCS infrastructures.

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