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Abstract

Carbon capture and storage (CCS) is an important solution to meeting climate targets set by United Nations and can potentially reduce 15 % of CO_2 emissions globally. CCS has been studied for over 20 years. However, its deployment rate is low due to challenges surrounding CCS costs for deployment and lack of awareness and importance of CCS in tackling climate change. To determine the viability of CCS chains, it is important to carry out techno-economic and environmental assessment over the lifecycle to identify potential cost optimization areas.

There are several tools that can be used for techno-economic and environmental impact assessment. Tool 1 was developed by a research institution in Norway. Two versions of this tool are available; Tool 1 (2012) and Tool 1 (2017). Tool 2 was developed by Energy consultancy agency based in the UK in partnership with research organizations and engineering companies in Netherlands and Norway. These tools were used to assess ongoing CCS Research and Development (R&D) activities and possible business cases to determine the accuracy of these tools and to identify the gaps within the tools. Tool 1 is able to assess different types of CO_2 transport options (onshore/offshore pipeline, shipping between harbors and direct shipping to an offshore site), while Tool 2, originally developed for the UK region, focuses more on ship transport option.

Three key themes were investigated within this study. The first theme consisted of assessing and analyzing shipping transport at different pressures (7 bara and 15 bara) from which low-pressure (7 bara) ship transport was identified to be a cost-optimal solution for business cases studied. Based on analysis of ongoing projects, using both versions of Tool 1 it was shown that for shorter distances pipeline transport was cost optimal, compared to ship transport. For longer distances, ship transport was shown to be a better option. However, Tool 1 calculated the carbon footprint of ship transport to be greater than pipeline transport of CO_2 regardless of the distance, mainly due to fuel consumption during travel and on-board reconditioning. Cost assessment results from Tool 2 provided a good insight on low pressure and medium pressure ship transport of CO_2, presenting low pressure ship option as more economical. However, since medium pressure ships have size restrictions (up to 10000 m^3) due to current design rules, ship sizes used by Tool 2 might not be feasible in practice. Tool 2 turned out to be more of a theoretical scenario tool based on different ship transport studies.

The second key theme consisted of investigating the potential benefits of re-using existing oil and gas infrastructure for transport and injection of CO_2. Re-using existing pipelines can potentially reduce emissions by over 80 % and give cost savings of over 85 % compared to new built pipelines and ship transport of CO_2 from one location to another provided that the challenges of re-use cases are overcome. Common parameters that have a significant impact on lifetime costs are flow rate, project duration, pipeline length and/or shipping distance according to parameter sensitivity analysis performed using Tool 1.

The third theme consisted of understanding the effect of pipeline dimensions on costs especially focusing on pipe diameter and wall thickness. For specific pipeline transport case, it is shown that changing pipeline diameter might have significant impact on total lifetime costs. For 10.75 and 12.75-inch pipeline, varying wall thickness in the range of ±50 % showed very limited benefit on costs of pipeline.

Overall, the study qualified Tool 1 for multicriteria analysis of CCS related projects compared to other publicly available tools. The results obtained using Tool 1 provided insights on areas of CO_2 transport chain, where cost optimization can occur and helped with selecting cost-optimal transport options for ongoing projects and business cases.

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Abbreviations

API:	American Petroleum Institute
CAPEX:	Capital expenditure
CCS:	Carbon capture and storage
CCUS:	Carbon capture utilization and storage
E&P:	Exploration and Production
EOR:	Enhanced Oil Recovery
FOK:	First-of-a-kind
GHG:	Greenhouse gas
ID:	Inner diameter
IO LCA:	Input-output life-cycle assessment
KPI:	key performance indicators
LP:	Low pressure
MP:	Medium pressure
MTPA:	Million tonne per annum also denoted at Mt_{CO2}/year
NOK:	Nth-of-a-kind (*NOK also represents Norwegian Krones. However, this document does not use the Norwegian currency)
O&G:	Oil and gas
O&M:	Operation and Maintenance
OD:	Outer diameter
OPEX:	Operating expenditure
R&D:	Research and Development
SRC:	Stavanger Research Centre
SDG:	Sustainable Development Goal
STL:	Submerged Turret Loading

1 Introduction

Ever since the Paris Climate Agreement signed in 2016 as part of United Nations Framework Convention on Climate Change (UNFCCC), there has been an increase need for Carbon Capture and Storage (CCS) to ensure that the long-term global average temperature does not increase more than 1.5 ^{o}C above pre-industrial levels *(Jakobsen, Roussanaly, Mølnvik, & Tangen, 2013*). Extensive research has been going on in the field of CCS globally to gain fundamental knowledge of the CCS chains, as well as develop technologies that would improve the functioning of CCS chains in order to fulfil its purpose of reduction of CO_2 emissions.

Many studies have published cost estimates of CCS chains or parts of the chain over the years. However, the results are difficult to compare due to large discrepancies in the assessed costs despite studies having similar hypothesis. The reason for such variation in cost estimates could possibly be due to differences in assumptions made for the analysis and methodologies used for cost assessment. CCS cost estimates performed in different geographical regions and selection of system boundaries result in this variation as well. CCS projects need to be proven economically and environmentally feasible, in order to bring it closer to commercial realization *(Jakobsen, Tangen, & Nordbø, 2008*). However, in order to be successful, they need to fulfil and satisfy a wide range of technical, economic, environmental and societal requirements.

A research organization based in Norway has developed an Excel based tool called Tool 1, for multi-criteria assessment of CCS chains. At the moment only several parties have been given access to this tool that are part of an international research collaboration on CCS since 2016. Such parties are research institutions, universities and major industrial partners. The main objective of this research collaboration on CCS is to fast-track deployment of CCS through innovation and overcoming barriers to become a leading CCS Centre globally. Tool 1 was developed under this research Centre and the purpose of the tool is to estimate the cost and environmental impact of CCS value chains . Two versions of this tool are currently available and is beneficial in identifying the potential cost optimization areas of the CO_2 transport system as well as aiding in selecting a cost-optimal transport option for certain cases.

Another techno-economic and environmental assessment tool was published in late 2018 by an energy consultancy agency based in the UK. It was commissioned in the UK for the purpose of estimating shipping costs of CO_2. This tool is named as Tool 2 within this report. The tool is limited to estimating the cost of shipping between harbors or direct shipping to an offshore site cost. It consists of a liquefaction/conditioning unit before export and the shipping export part.

In the current research an assessment of the two tools described above have been done. The scope of the work has been limited to cost and environmental impact analysis of CO_2 transport systems. Two versions of Tool 1 and one version of Tool 2 were used for the analysis.

1.1 Objectives

The main objectives of the thesis were:

- To assist Total Exploration & Production (E&P) Norge CCS R&D team with topics related to CO_2 transport by assessing currently available tools on techno-economic and environmental criteria of CCS related projects.
- To help with identifying and analyzing the gaps in the accuracy of the CCS simulation tools and potential improvements.
- To use the tool to assess future business cases.
- To quantify the potential benefits in terms of cost savings and environment of the ongoing R&D activities.

1.2 Company overview

Total E&P Norge is a subsidiary of Total Group based in Stavanger, Norway for more than 50 years, responsible for Total's exploration and production activities on the Norwegian Continental Shelf. Stavanger Research Centre (SRC) is one of five R&D centres of Total E&P branch located outside of France. SRC main activities are on the following topics: Drilling & Wells, low carbon and CCUS unit, deep offshore and sustainable development.

1.3 Context and Thesis outline

Aligning with the ambitious target of staying below the global temperature rise of 2 ^oC, Total is committed to promoting Sustainable Development Goals (SDGs) defined by United Nations. To tackle the challenge of climate change, the group has integrated climate into its four strategic focuses: Natural gas, low carbon electricity, petroleum products and carbon neutrality. Total is committed to develop first industrial hubs for commercial CCS and help carbon-intensive industries like cement and steel manufacturing reduce their CO_2 emissions through CCS operation. *(Total Group, 2019)*

Total has heavily invested in CCS related activities in last decade out of which a third of them are taking place in Norway. Total has invested in a project connected to the Norwegian Continental Shelf (NCS) which is a large-scale CCS plan developed with Equinor and Shell to transport in the first phase 1.5 Mt CO_2 per year. The success of this project could open doors to industrial development of CCS within Norway and throughout the region and Europe.

The focus of this thesis has been analysis of CO_2 transport options (both by ship and by pipeline) through assessment of various projects and business cases. The purpose of the work is to reveal the financial and environmental interest of developing CCS systems with lowest possible CO_2 emissions.

The main reasons why CCS is required, and the challenges faced with CCS currently are covered in the second chapter. The third chapter of the report introduces the techno-economic and environmental assessment tools that are public or restricted. Quick cases are simulated using those tools and the results are presented and compared to understand the difference in the functionality and accuracy of the tools.

The fourth chapter represents the first theme of the thesis, which is medium pressure and low-pressure ship transport. This chapter introduces the projects related to shipping at different transport pressures. and comparison of costs and environmental assessment results to identify the optimal transport conditions.

The fifth chapter explores a new theme evaluation, cases of reusing pipeline infrastructure for CO_2 transport as part of ongoing R&D interests. The chapter explores a project initiated by Total E&P R&D team and presents the results obtained using the simulation tools for this project.

The sixth chapter is the final theme of the thesis work and it focuses on the effects of pipeline dimensions on the costs of CO_2 transport.

The last three chapters of the report summarize the key findings and identify the gaps in Tool 1 after the assessments have been completed. The chapters also include recommendations on future work related to techno-economic and environmental assessments of CO_2 transport chains and final conclusions. Most of the detailed results and tables can be found in the appendices attached at the end of the report.

2 Theory

2.1 Importance of CCS

To meet the global energy demands, human population would remain dependent on oil and gas for decades to come. Climate researchers agree that CO_2 is a greenhouse gas which stays in the atmosphere forming a blanket that prevents heat radiation escaping the atmosphere. As a result, it causes Earth's temperature to rise. It is an unrealistic solution to completely stop oil and gas production to save the environment, however a possible solution is to reduce CO_2 equivalent emissions from industrial activities through CCS programs. Cement and Steel industry are also big contributors of CO_2 by generating between 7 and 9 % of global total annually, which are being addressed in current CCS programs. EU Commission released its 2050 Climate Strategy report in November 2018 stating that globally CO_2 emissions should be reduced by 5 gigatons per year *(Benjaminsen, 2019)* and through CCS around 15 % of the global emissions can potentially be eliminated *(Gassnova, u.d.)*. Without CCS, the challenge of achieving climate objectives will become greater.

2.2 Challenges with CCS

CCS technologies are expensive since they are not widely available and have not matured. Over the years the costs of such technologies could decrease. Lack of governmental funding and support is resulting in slow growth of CCS deployment. To deploy CCS projects, a strong and continued support is required from governments to develop CCS that includes incentives and subsidies to encourage development of CCS. Lack of incentives for public and private investors is another challenge that could be met by making CCS profitable from CO_2 sales for enhanced oil recovery (EOR) purposes or other utilization purposes. *(Todd, 2019)*

There is a lack of knowledge on the geological characteristics for storage of CO_2 due to limited experience and data. Therefore, CCS researchers need to explore potential CO_2 storage locations and set up testing projects to identify these areas. There is also lack of knowledge about CCS amongst the public due to poor communication strategy. In short, there is a high level of uncertainty surrounding feasibility of CCS, which can only be overcome through successfulness of several CCS related projects around the world.

3 Existing tools

Within this chapter the fundamentals behind techno-economic and environmental assessment tools for CCS chains are explored. The first tool is called Tool 1, which is being licensed from a research organization based in Norway by Total E&P Norge. Two versions of this tool are available, Tool 1 (2012) and Tool 1 (2017), and both versions have been evaluated within this thesis. The second tool used is a publicly available tool and is referred to as Tool 2 within this report.

3.1 Tool 1 (2012)

A research organization based in Norway developed a methodology and a common framework to assess CCS chains based on multiple criteria. A techno-economic and environmental assessment tool referred to as Tool 1 (2012) was developed which allows cost evaluation and comparison of different CCS chains/components. It has a modular structure that simulates the CCS chain configurations. The purpose of such a tool is to help decision makers select the best alternatives for CCS chain and help bring CCS closer to commercial realization. From an R&D perspective it can easily and quickly estimate costs and emissions for CCS related projects or cases.

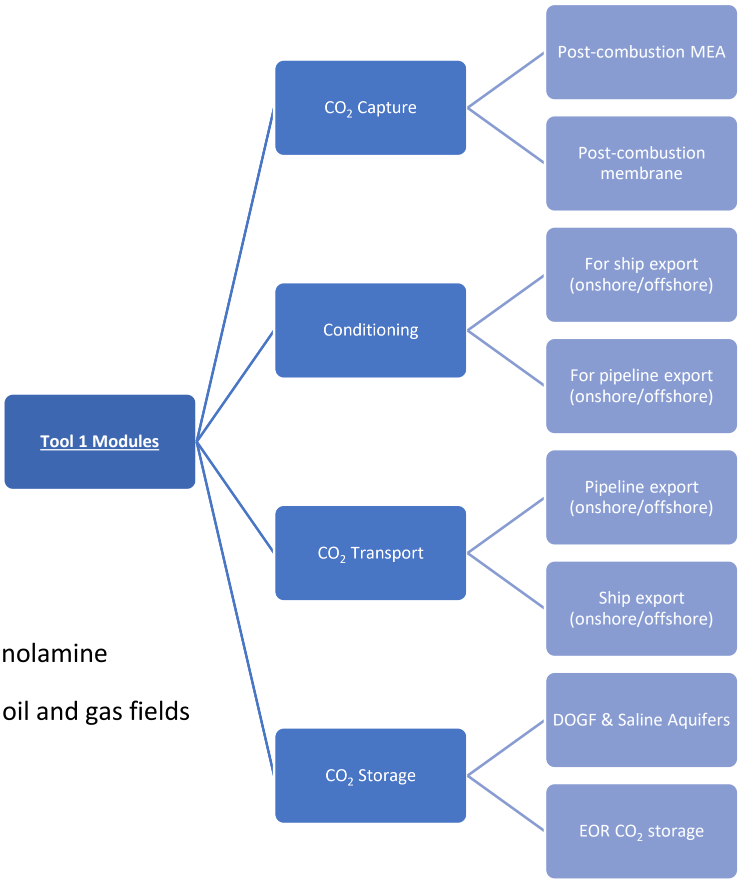
Tool 1 (2012) can be used to develop case studies that could guide on different aspects of CCS deployment such as technology development, effect of economic parameters and political and regulatory issues. The tool allows user to compare technologies within a single chain, compare different chain designs and perform sensitivity analysis. The results can be used for comparing CCS technology with other solutions such as renewables.

The tool has a modular structure presented in Figure 1**Error! Reference source not found.**. The modules are CO_2 capture, conditioning, transport and storage module which can be connected to make a CCS chain. The modules work together to perform an integrated techno-economic and environmental assessment of the chains (refer to Figure 2). Basic input or design parameters are defined in the tool depending on the specific case (e.g. flow rate, distance, lifetime, shipping speed). The input data is used within the tool for a technical assessment of the chain/module. The technical assessment is based on modelling from Aspen Plus, Aspen HYSYS and modelling from literature. The mass and energy balances obtained from Aspen lead to size of equipment required and the utilities consumption. Aspen process economic analyzer and data from literature are used to perform cost assessment. Investments costs, Operations & Maintenance (O&M) and utility costs are obtained from the cost evaluation. Lastly a green-house gases (GHG) assessment is performed by using a hybrid life-cycle assessment (LCA) method which uses climate impact factors from EcoInvent Life Cycle Inventory and IO LCA method Carnegie Mellon University database. In short, system parameters and independent variables are used as input in Tool 1 resulting in economic outputs and emissions (Figure 3).

Within this report, the main focus has been the CO_2 Transport module. However, whenever necessary the Conditioning module has been used as well. CO_2 transport module has four submodules:

1) Shipping between harbors
2) Shipping directly to an offshore site
3) Offshore pipeline
4) Onshore pipeline

Conditioning module has four similar submodules.



MEA: Monoethanolamine

DOGF: depleted oil and gas fields

Figure 1: Structure of Tool 1 modules

Figure 2: Methodology of Tool 1

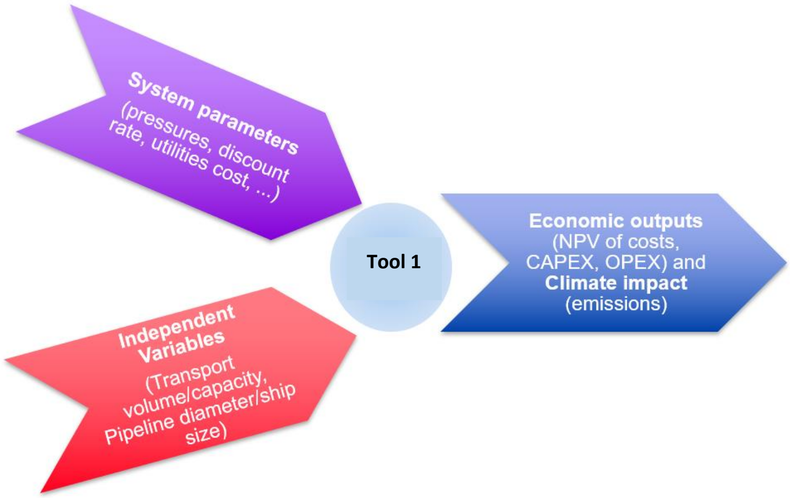


Figure 3: Tool 1 process

3.1.1 Onshore pipeline transport

CO_2 is captured and delivered at 1 atm and 25 °C to the conditioning unit, where CO_2 will go through 4 compression stages and pumping to reach the desired purification and conditioning for export (*Aspelund & Jordal, 2007*)[1]. Cooling duty required is obtained from Aspen HYSYS and converted into a model that is a function of power model coefficient (which is specifically calculated for each compressor and pump), annual flow rate, change in pressure between inlet and outlet of conditioning unit, operating hours and adiabatic efficiency. Cooling water requirement is simply modelled using heat transfer laws and it is proportional to a constant and annual volumetric flow rate *(SR & ESH, 2012)*[2].

The capital expenditure (CAPEX) of onshore pipeline in Tool 1 (2012) with design pressure of 150 bar is 47377 $€_{2009}$/inch/km. This is obtained from literature on North-Western Europe CO_2 infrastructure report (*Mikunda, et al., 2011*). Factor estimation method is used to estimate the CAPEX of process equipment for varying capacities and costs by multiplying the investment cost with direct and indirect cost factors estimated using Aspen Process Economic Analyzer. Fixed operating expenditure (OPEX) is set at 6 % of CAPEX per year for process units while for onshore pipeline it was set as 6633 €/km/year *(Mikunda, et al., 2011).* Variable OPEX is set as a function of CO_2 flow rate and estimated using process simulations.

3.1.2 Offshore pipeline transport

Similar to the onshore pipeline transport option, the CO_2 is captured and delivered at 1 atm and 25 °C to the conditioning unit where CO_2 will go through 4 compression stages and pumping to reach desired purification and conditioning for export *(Aspelund & Jordal, 2007*). Cooling duty required is obtained from Aspen HYSYS and converted into a model that is a function of power model coefficient (which is specifically calculated for each compressor and pump), annual flow rate, change in pressure between inlet and outlet of conditioning unit, operating hours and adiabatic efficiency. Cooling water

[1] Dehydration unit is not included in Tool 1 because it assumes that the inlet stream is pure CO_2
[2] Dehydration unit is not included in Tool 1 because it assumes that the inlet stream is pure CO_2

requirement is simply modelled using heat transfer laws and it is proportional to a constant and annual volumetric flow rate. *(SR & ESH, 2013)*

The offshore pipeline has a maximum design pressure of 200 bar. Offshore pipeline transport consists of a flexible pipeline riser to transport CO_2 from shore to the bottom of the sea and then the actual pipeline itself *(SR & ESH, 2013*). Pipeline is designed according to American Petroleum Institute (API) specification 5L standard "Specification for Line Pipe" *(American Petroleum Institute, 1990)*. Pressure drops are calculated using steady state equations for incompressible flow under isothermal conditions and derived from Fanning equation with no elevation effect (*SR & ESH, 2013*).

The CAPEX of offshore pipeline in Tool 1 (2012) with design pressure of 200 bar is 71065 $€_{2009}$/inch/km based on literature on North-Western Europe CO_2 infrastructure report *(Mikunda, et al., 2011)*. Factor estimation method is used to estimate the CAPEX of process equipment for varying capacities and costs by multiplying the investment cost with direct and indirect cost factors estimated using Aspen Process Economic Analyzer. Fixed OPEX is set at 6 % of CAPEX per year for process units while for offshore pipeline, it is set at 6633 €/km/year (*Mikunda, et al., 2011*). Similar to the onshore pipeline case, the variable OPEX is set as a function of CO_2 flow rate and estimated using process simulations.

3.1.3 Shipping to an offshore site

CO_2 from capture site is conditioned to reach 6.5 bara and -50.3 °C (liquid state) for it to be exported by ship *(Aspelund & Jordal, 2007)*. Conditioning unit consists of 3 compression stages and ammonia cooling cycle to lower the temperature. Shipping export part consists of cryogenic temporary buffer storage, the actual ship transport, a ship cryogenic buffer storage close to storage location that includes on-ship reconditioning and a flexible pipeline riser. Buffer storage size is taken to be equal to the ship size selected while a Submerged Turret Loading (STL) system and spread mooring system is used at the storage site *(European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2011*).

Shipping fuel consumption is estimated from literature while reconditioning on ship are simulated using Aspen HYSYS to model the electricity consumption onboard *(Roussanaly, Bureau-Cauchois, & Husebye, 2012)*. Shipping CAPEX and loading and unloading facilities CAPEX and OPEX are used from literature presented by Knoope et al. (*Knoope, Ramirez, & Faaij, 2015*).

3.1.4 Shipping between harbors

Conditioning before shipping export for both types of shipping are similar[3]. In this case the conditioned CO_2 goes to a cryogenic temporary buffer storage from where it is loaded onto the ships for transport which unload CO_2 at another cryogenic buffer storage onshore. CO_2 is then reconditioned onshore to be exported via pipeline. All the other data are obtained the same way they are obtained for direct shipping module except that the electricity consumption estimated based on Aspen HYSYS simulations are slightly different[4].

[3] There is a conditioning submodule for shipping between harbors and a conditioning submodule for shipping directly to an offshore site

[4] Reconditioning onshore for shipping between harbors case consumes more electricity (due to increasing pressure of CO_2 to match pipeline export pressure) than on-ship reconditioning for direct shipping (which needs to increase CO_2 conditions to match wellhead pressure).

3.2 Tool 1 (2017)

A recent version of Tool 1 which was updated in 2017 was provided to Total E&P Norge in March 2020. The tool visually looks like its predecessor however some improvements have been made in capture and transport modules. Overall, formats were updated (such as the layout of Parameters sheet in Tool 1 module), and the costs were updated to reflect 2016 levels. Some of the main updates relevant to this report are described in the following paragraphs.

The following improvements were made in Tool 1 (2017) compared to Tool 1 (2012):

- Improved cost model for onshore and offshore pipeline based on Knoope et al. *(Knoope, Guijt, Ramirez, & Faaij, 2014)*, where the cost model is split into various elements: material cost, labor cost, onshore-offshore landfall cost, Right-Of-Way cost and miscellaneous costs.
- Pipeline module includes different terrain factors into consideration when calculating costs.
- Fixed annual OPEX of pipelines (for both onshore and offshore) is reduced to 1.5 % of CAPEX (from 9 % for offshore pipelines and 14 % for onshore pipelines).
- More input parameters are added to the parameters sheet. In addition, user is given more flexibility in terms of changing set parameters (in the case of pipeline and ship module in Tool 1).
- Additional ship sizes have been added along with user specific ship characteristics.

3.3 Tool 2 (2018)

In the tool the inlet CO_2 to the liquefaction unit can either be pre-pressurized (70-100 bar) or non-pressurized (1-2 bar) which undergoes processes to reach the desired output conditions. Tool 2 is based on_: compiled literature data on CO_2 liquefaction that considers transport pressure option of low, medium and high. A short-listed literature data on liquefaction CAPEX, OPEX and energy requirement were averaged leading to a liquefaction cost assumption that Tool 2 have used in the model (refer to Table 1). Fixed OPEX was set as 10 % of liquefaction CAPEX per year and liquefaction fuel price is set as £ 0.08/kWh in Tool 2 which is for the electricity. *(EE & others, 2018)*

Table 1: Liquefaction cost assumptions used in Tool 2[5], [6]

Transport pressure	Inlet pressure type of CO_2	Specific CAPEX[7] (£/t_{CO2}/year)	Fixed OPEX (% CAPEX/year)	Energy required (kWh/t)
Low P	Pre-pressurized	9.8	10	24.6
Low P	Non-pressurized	19.5	10	104.2
Medium P	Pre-pressurized	7.6	10	19.6
Medium P	Non-pressurized	15.1	10	83.1
High P	Pre-pressurized	4.9	10	16.6
High P	Non-pressurized	9.7	10	70.3

[5] The British Pounds are converted to Euro using the following exchange rate £ 1 = 0. 88 €
[6] (EE & others, 2018)
[7] Specific CAPEX is an assumption used in Tool 2 which comes from averaging liquefaction CAPEX data from literature.

The buffer storage size before export is 20 % greater than ship capacity and the specific cost of storage is found from a list of literature data (Refer to page 81 for the storage assumptions used in Tool 2). Loading and unloading CAPEX and OPEX are determined by averaging the data from various literature to select specific loading/unloading CAPEX as £ 1.4/t_{CO2} per year and OPEX as 3 % of CAPEX per year[8]. Ship CAPEX in Tool 2 is estimated by performing regression analysis on CAPEX values found in literature for Low Pressure (LP) and Medium Pressure (MP) ship transport. A power regression curve can be seen in Figure 4 that can be used to estimate ship CAPEX based on its cargo capacities. Ship fixed OPEX is set at 5 % of CAPEX per year in the tool. Harbor fees and ship fuel consumption are calculated by regression analysis on data found from literature as shown in Figure 4. Onshore and offshore reconditioning costs are based on literature *(EE & others, 2018).*

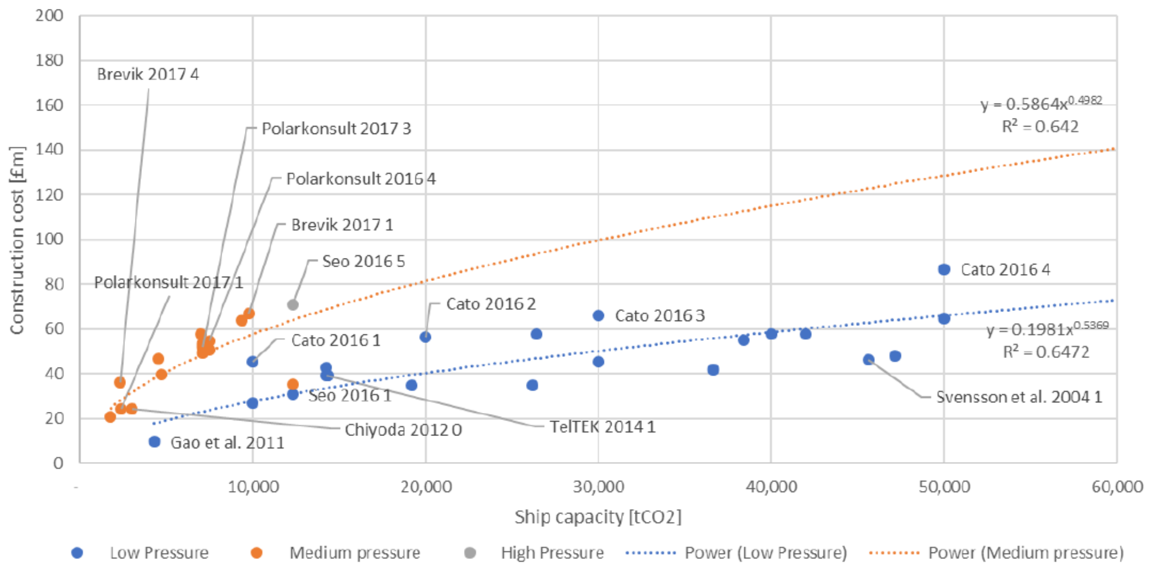


Figure 4: Ship CAPEX regression analysis of Tool 2[9]

3.4 Comparison between Tool 1 & Tool 2

Purpose of the work in this section was to qualify the current tools available on techno-economic and environmental assessment of CCS related cases, as well as to identify and analyze the gaps in the accuracy of these tools. Three tools were evaluated: Tool 1 (2012), Tool 1 (2017) and Tool 2 (2018).

3.4.1 Tool 1 (2012) vs Tool 2

A thorough analysis was performed for all the transport modules within Tool 1 (2012) and Tool 2 [10]. The main parameters that were varied were lifetime of the project and the flow rates. The distance was fixed at 600 km, flow rates were analyzed as 0.5, 1, 5 and 10 MTPA of CO_2 and the lifetimes were 10 years, 20 years and 40 years.

[8] Loading and unloading CAPEX is assumed in Tool 2 as £ 1.4/t_{CO2} per year and OPEX as 3 % of CAPEX per year.
[9] (EE & others, 2018)
[10] Tool 2 does not have onshore pipeline transport module

3.4.1.1 *Shipping between harbors*

For shipping between harbors, the lifetime costs given by each of the tools are presented in Table 2. For each flow rate and each lifetime, the difference between Tool 2 and Tool 1 (2012) total lifetime cost results varied between 15 - 23 % range. In absolute values, as the flow rate is increased from 0.5 MTPA to 10 MTPA, Tool 1 (2012) gives higher results in terms of magnitude than Tool 2. As the project lifetime increases from 10 years to 40 years at low flow rate such as 0.5 MTPA, the lifetime costs given by both Tool 1 (2012) and Tool 2 increases by almost 200 % compared to the lifetime costs over a 10-year period. This represents an increase in 350 M€ for Tool 1 (2012) and 280 M€ for Tool 2.

Figure 5 and Figure 6 represent the cost splits obtained from Tool 2 and Tool 1 (2012) for shipping between harbors case (including conditioning before export) for 0.5 MTPA 10 years and 40 years lifetime respectively. In both figures it is observed that Tool 1 (2012) gives, in general higher costs compared to Tool 2 except for investment costs (e.g. Ship CAPEX). The difference in the lifetime costs between the tools mainly comes from conditioning CAPEX and OPEX. The reason for that is Tool 2 uses electricity to provide energy to the liquefaction unit while Tool 1 (2012) uses fuel therefore Tool 2 would have a lower OPEX. Tool 1 (2012) shows almost a double liquefaction CAPEX compared to Tool 2. The liquefaction cost in Tool 1 is based on Aspen HYSYS simulation of liquefaction unit, where the investments costs of process equipment are obtained from Aspen HYSIS economic analyzer software. Tool 2 on the other hand uses liquefaction CAPEX that has been averaged from a list of literature data.

Table 2: Difference between lifetime cost results from Tool 1 (2012) and Tool 2 for 600 km shipping between harbors case[11]

Flow rate (MTPA)	Year	Total lifetime costs (M€) Tool 1 (2012)	Total lifetime costs (M€) Tool 2	Difference between Tool 1 (2012) and Tool 2 (M€)	% difference between Tool 1 (2012) and Tool 2 [12]
0.5	10	176	146	30	21 %
	20	293	239	53	22 %
	40	526	427	99	23 %
1	10	284	238	45	19 %
	20	490	405	84	21 %
	40	903	739	163	22 %
5	10	1222	1006	216	21 %
	20	2130	1737	393	23 %
	40	3942	3197	744	23 %
10	10	2194	1907	286	15 %
	20	3913	3333	580	17 %
	40	7350	6184	1165	19 %

[11] Distance is 600 km; flow rate and lifetime are varied, and the transport type is shipping between harbors including conditioning before export costs.
[12] Tool 2 cost values are taken as reference points

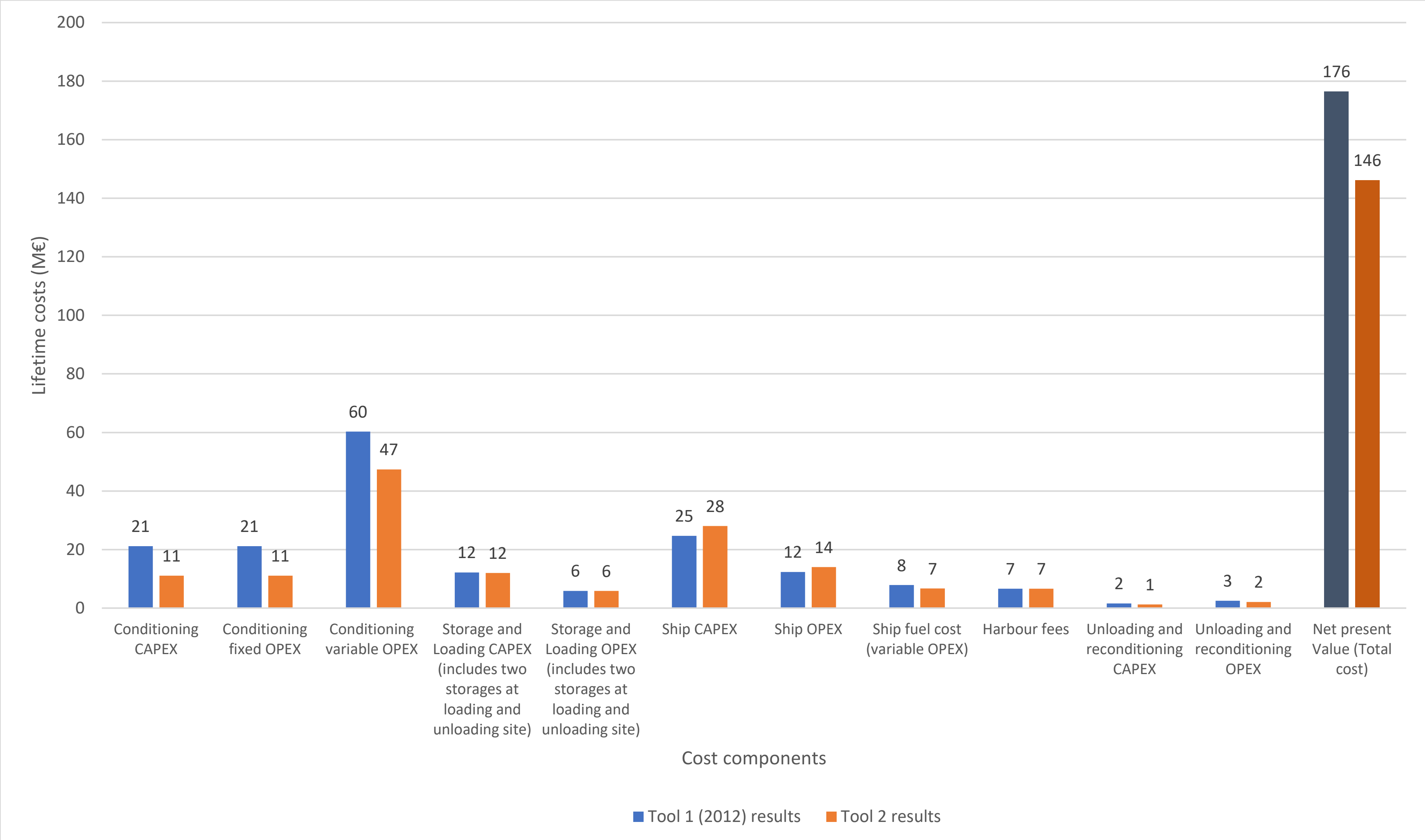


Figure 5: Conditioning and shipping between harbor costs from Tool 1 (2012) and Tool 2 for 0.5 MTPA, 600 km and 10 years

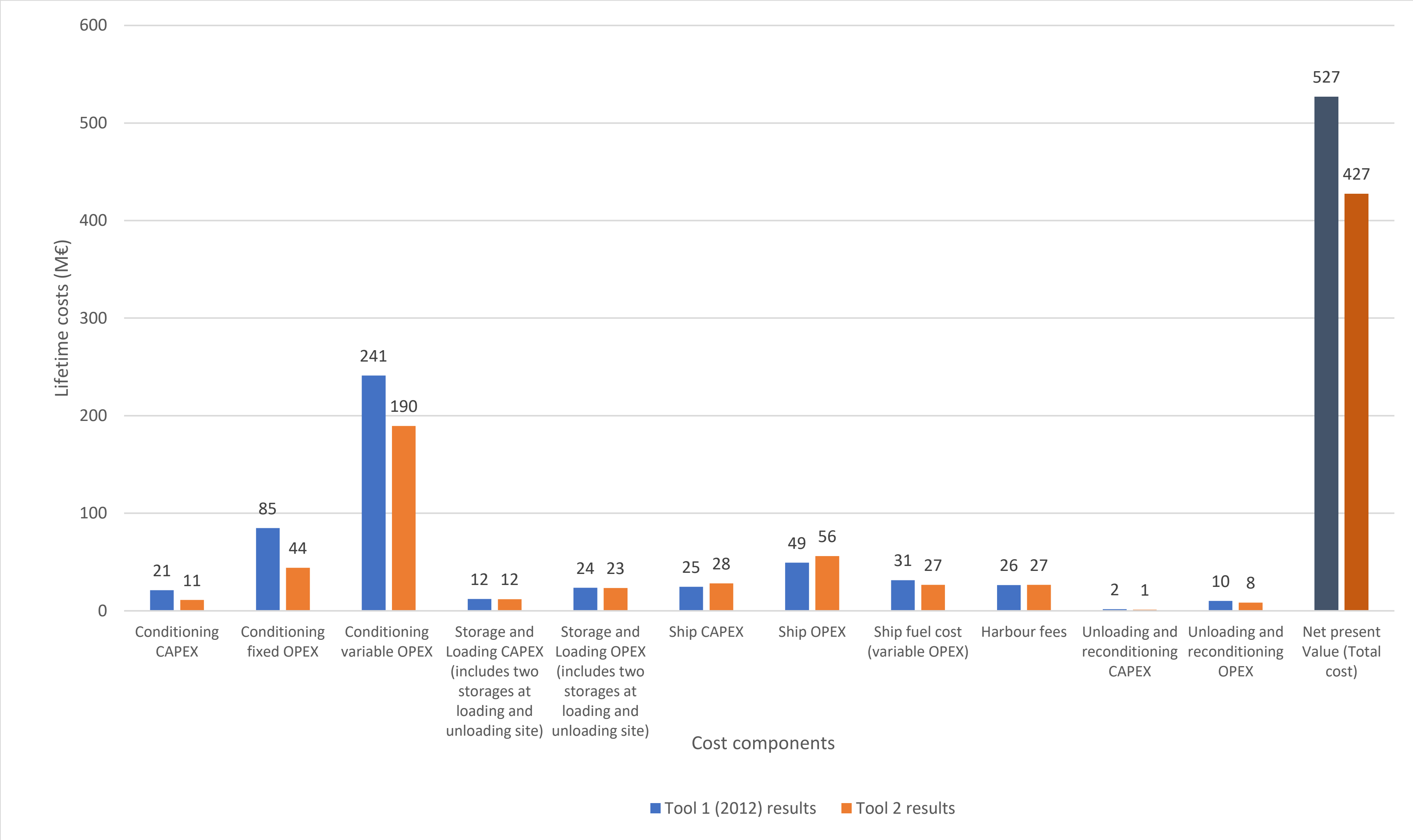


Figure 6: Conditioning and shipping between harbor costs from Tool 1 (2012) and Tool 2 for 0.5 MTPA, 600 km and 40 years

3.4.1.2 *Shipping to an offshore site*

For shipping to an offshore site transport option to a potential storage location, the lifetime costs given by each of the tools are presented in Table 3Table 2. For each flow rate and each lifetime, the difference between Tool 2 and Tool 1 (2012) results varied within 10 - 24 % range. In absolute values, as the flow rate is increased from 0.5 MTPA to 10 MTPA, Tool 1 (2012) gives higher results in terms of magnitude than Tool 2. As the project lifetime increases from 10 years to 40 years at low flow rate such as 0.5 MTPA, the lifetime costs given by both Tool 1 (2012) and Tool 2 increase by almost 175 % and 180 % compared to the costs over a 10-year period.

The difference in the lifetime costs between the tools mainly comes from conditioning CAPEX, OPEX and Reconditioning on-ship CAPEX. The reason for that is Tool 2 uses electricity to provide energy to the liquefaction unit and reconditioning unit while Tool 1 (2012) uses heavy fuel. Therefore, Tool 2 would have a lower OPEX. Tool 1 (2012) shows almost a double liquefaction CAPEX compared to Tool 2. The liquefaction cost in Tool 1 is based on Aspen HYSYS simulation of liquefaction unit, where the investments costs of process equipment are obtained from Aspen HYSIS economic analyzer software. Tool 2 on the other hand uses liquefaction CAPEX that has been averaged from a list of literature data.

Table 3: Difference between lifetime cost results from Tool 1 (2012) and Tool 2 for 600 km shipping to an offshore site case[13]

Flow rate (MTPA)	Year	Total lifetime costs (M€) Tool 1 (2012)	Total lifetime costs (M€) Tool 2	Difference between Tool 1 (2012) and Tool 2 (M€)	% difference between Tool 1 (2012) and Tool 2[14]
0.5	10	205	165	40	24 %
	20	325	264	61	23 %
	40	564	461	103	22 %
1	10	329	281	47	17 %
	20	537	455	81	18 %
	40	954	804	149	19 %
5	10	1199	1038	161	16 %
	20	2075	1779	295	17 %
	40	3826	3262	563	17 %
10	10	2179	1973	205	10 %
	20	3846	3414	431	13 %
	40	7179	6297	881	14 %

[13] Distance is 600 km; flow rate and lifetime are varied, and the transport type is shipping to an offshore site including conditioning before export costs.
[14] Tool 2 results are used as reference

3.4.1.3 *Offshore pipeline*

For offshore pipeline transport system, the lifetime costs given by each of the tools are presented in Table 4. A key point about offshore pipeline transport module is that Tool 2 does not include costs for conditioning before pipeline export. However, it does give a compressor cost. So, to make the comparison fair, only the transport results are compared between Tool 1 (2012) and Tool 2. For each flow rate and each lifetime, the difference between Tool 2 and Tool 1 (2012) results varied between -6 to 11 % . In absolute values, as the flow rate is increased from 0.5 MTPA to 10 MTPA, Tool 1 (2012) gives higher cost results than Tool 2 except for the case of 5 MTPA. At 5 MTPA flow rate, Tool 2 gives higher offshore pipeline costs than Tool 1 (2012) due to Tool 2 selecting larger pipeline diameter than Tool 1 (2012). For the flow rates investigated, when the project lifetime increases from 10 years to 40 years , the lifetime costs given by Tool 1 (2012) and Tool 2 increase by approximately 29 % and 27 % respectively. The difference in the lifetime costs between the tools mainly comes from pipeline CAPEX, due to a lower aggregated pipeline CAPEX in Tool 2 compared to Tool 1 (2012). (EE & others, 2018)

Table 4: Difference between lifetime cost results from Tool 1 (2012) and Tool 2 for 600 km offshore pipeline case[15]

Flow rate (MTPA)	Year	Total lifetime costs (M€) Tool 1 (2012)	Total lifetime costs (M€) Tool 2	Difference between Tool 1 (2012) and Tool 2 (M€)	% difference between Tool 1 (2012) and Tool 2[16]
0.5	10	449	409	39	10 %
	20	492	447	46	10 %
	40	579	521	58	11 %
1	10	586	573	12	2 %
	20	642	625	17	3 %
	40	756	729	26	4 %
5	10	928	983	-54	-6 %
	20	1021	1072	-51	-5 %
	40	1205	1251	-45	-4 %
10	10	1349	1310	39	3 %
	20	1483	1429	54	4 %
	40	1750	1667	83	5%

[15] Distance is 600 km; flow rate and lifetime are varied, and the transport type is offshore pipeline which does NOT include booster pump and conditioning costs before export

[16] Tool 2 results are taken as reference

4 Business case from North of France

This section of the report covers the techno-economic and environmental assessments conducted for some parts of a business case in North of France, which Total E&P Norge is involved in. The assessments include a section that covers and compares CO_2 ship transport at 7 bara and 15 bara. This assessment is conducted for one of the concepts from the project.

4.1 Introduction to business case, MP versus LP ship transport and a project connected to Norwegian Continental Shelf (NCS)

The idea behind the business case was to design a CCS chain from Northern region of France to a potential storage location in the North Sea and define a cost optimal transport method. CO_2 was captured and conditioned at an industrial site in France. Three alternatives were evaluated and assessed from economic point of view by Total E&P Norge R&D in order to compare and select the most appropriate option. The first alternative was a 'stand-alone' independent study that was compared to other alternatives and it studied the costs of CO_2 transport by offshore pipeline and by ship for varying distances representing different locations for the storage site. The second alternative was to connect to the project within NCS where the captured CO_2 from North of France was stored in a location in the North Sea. The third and last alternative was to connect to a project in Netherlands where CO_2 was transported to Dutch North See coast and stored via a potential collaborative project with the host.

This report includes an important assessment of Medium pressure (MP) versus Low pressure (LP) CO_2 ship transport for the second alternative of the business case, which is being studied within Total E&P Norge CO_2 transport team. Currently 15 bara (MP) pressure is being used to transport food-grade CO_2 and this is what is considered for upcoming projects. LP transport is at 7 bara is being looked at as an optimization since it will allow a larger CO_2 transport capacity per ship. There are no LP ships in the world, so the studies involving LP ships are theoretical or are used for R&D purpose.

4.2 Objectives

The objectives of this work performed in this section were the following:

- To investigate the feasibility of using Tool 1 to perform techno-economic and environmental assessment of projects Total E&P are currently a part of.
- To determine a cost-optimal transport option for the projects and business case.
- To identify the limitations in Tool 1 by comparing the two versions with each other and with another publicly available tool for the work performed in this section
- To investigate and understand the difference in techno-economic and environmental results between 7 bara (LP) and 15 bara (MP) ship transport as part of a business case.

4.3 Case description & Methods

4.3.1 Business case from North of France: Analysis of alternatives using Tool 1 (2012), Tool 1 (2017) & Tool 2

Three alternatives were investigated under the business case and analyzed using both versions of Tool 1 (2012 & 2017) and Tool 2.

4.3.1.1 *Alternative #1: Stand-alone study – Offshore pipeline vs direct shipping (LP)*

In this alternative, 1 MTPA, 4 MTPA and 10 MTPA of CO_2 is transported via offshore pipeline or ship at 7 bara (low pressure ship transport). These options are studied and compared for distances from 100 km to 1000 km using both versions of Tool 1.

The following inputs were used in Tool 1 (2012)[17]:

- Offshore pipeline
  - Transport rate: 1, 4, 10 MTPA
  - Project lifetime 15 years
  - Pipe length: 100-1000 km
  - Inlet pressure: varies between 100 and 200 bar
  - Outlet pressure: 80 bar
  - Cost of steel: 1800 €/ton
  - Real discount rate: 7 %

- Direct shipping
  - Transport rate: 1, 4, 10 MTPA
  - Project lifetime: 15 years
  - Ship size: 21825, 30555 **or** 39285 m^3
  - Shipping distance: 100-1000 km
  - Ship speed: 26 km/hour
  - Real discount rate: 7 %
  - Ship utilization rate: 85 %

The following inputs were used in Tool 1 (2017)[18]:

- Offshore pipeline
  - Transport rate: 1, 4, 10 MTPA
  - Project lifetime 15 years
  - Pipe length: 100-1000 km
  - Inlet pressure: varies between 100 and 200 bar
  - Outlet pressure: 80 bar
  - Cost of steel: 1800 €/ton
  - Real discount rate: 7 %

[17] All ship transport using Tool 1 (2012) are at pressures of 7 bara (LP)
[18] All ship transport using Tool 1 (2017) are at pressures of 7 bara (LP)

- Direct shipping
    - Transport rate: 1, 4, 10 MTPA
    - Project lifetime: 15 years
    - Ship size: varies between 3870 to 38225 m^3 [19]
    - Shipping distance: 100-1000 km
    - Ship speed: 26 km/hour
    - Real discount rate: 7 %
    - Ship utilization rate: 85 %

4.3.1.2 *Alternative #2A: Plug-in Norwegian Continental Shelf (NCS), Norway – Offshore pipeline vs direct shipping (LP) and Ship transport (MP vs LP)*

A distance is estimated between North of France and a location in the North Sea to represent the transporting distance required to transport CO_2 from capture site to a point in the Norwegian Continental Shelf (NCS) for permanent storage. Both versions of Tool 1 were used to analyze offshore pipeline and ship transport (LP ship transport at 7 bara) for this option and the results were compared with each other to identify the cost optimal transport method. The second part of this alternative was simulation of this case using Tool 2. Shipping between harbors (North of France to West Coast of Norway) and direct shipping to an offshore site (North of France to a point in the NCS) were compared using Tool 2 where both MP and LP ship transport were assessed.

The following inputs were used in Tool 1 (2012)

- Offshore pipeline
    - Transport rate: 1 MTPA
    - Project lifetime 15 years
    - Pipe length: 1100 km
    - Optimum pipeline diameter: 12.75-inch OD
    - Inlet pressure: 155 bar
    - Outlet pressure: 80 bar
    - Cost of steel: 1800 €/ton
    - Real discount rate: 7 %

- Direct shipping
    - Transport rate: 1 MTPA
    - Project lifetime: 15 years
    - Ship size: 21825 m^3 (2 ships)
    - Shipping distance: 1100 km
    - Ship speed: 26 km/hour
    - Real discount rate: 7 %
    - Ship utilization rate: 85 %

[19] Maximum ship size considered in Tool 1 (2017) was 39285 m^3

The following inputs were used in Tool 1 (2017):

- <u>Offshore pipeline</u>
  - Transport rate: 1 MTPA
  - Project lifetime 15 years
  - Pipe length: 1100 km
  - Optimum pipeline diameter: 12.75-inch OD
  - Inlet pressure: 155 bar
  - Outlet pressure: 80 bar
  - Cost of steel: 1800 €/ton
  - Real discount rate: 7 %

- <u>Direct shipping</u>
  - Transport rate: 1 MTPA
  - Project lifetime: 15 years
  - Ship size: 7500 m^3 (2 ships)
  - Shipping distance: 1100 km
  - Ship speed: 26 km/hour
  - Real discount rate: 7 %
  - Ship utilization rate: 85 %

The following inputs were used in Tool 2 (2018)[20]:

- Shipping distance: 1100 km
- Transport rate: 1 MTPA
- Project lifetime: 15 years
- Ship size: 20000 t_{CO2}
- Ship speed: 27.78 km/hour
- Real discount rate: 7 %
- LP transport: 7 bara
- MP transport: 15 bara
- Ship utilization rate: 100 %

4.3.1.3 Alternative #2B: Project connected to NCS - Shipping between harbors (MP vs LP)

Alternative #2B of the business case was re-simulated for low pressure and medium pressure ship transport for a 25-year lifetime in Tool 1 (2017) and Tool 2. This alternative allowed comparison of MP vs LP shipping based on a fixed distance. Tool 1 (2012) was not used due to the complexity of manipulating the parameters to mimic MP transport. The distance selected was 1000 km which represented the distance from North of France to West Coast of Norway. The flow rate selected was 1 MTPA and the transport option selected was **shipping between harbors**.

The following inputs were used in Tool 1 (2017) for LP and MP transport analysis:

- Transport rate: 1 MTPA
- Project lifetime: 25 years
- Ship size: 7500 m^3

[20] These inputs are used for both types of ship transport: shipping between harbors and direct shipping to an offshore site

- Number of ships: 2
- Shipping distance: 1000 km
- Ship speed: 27.78 km/hour
- Real discount rate: 8 %
- LP transport: 7 bara
- MP transport: 15 bara[21]
- Ship utilization rate: 85 %

The following inputs were used in Tool 2 (2018):

- Shipping distance: 1000 km
- Transport rate: 1 MTPA
- Project lifetime: 25 years
- Ship speed: 27.78 km/hour
- Ship size for LP transport: 7500 m^3
- Ship size for MP transport: 7500 m^3
- Number of ships: 2
- Real discount rate: 8 %
- LP transport: 7 bara
- MP transport: 15 bara
- Ship utilization rate: 100 %

4.3.1.4 *Alternative #3: Plug-in project in Netherlands- Offshore pipeline vs shipping between harbors (LP)*

A distance was estimated between North of France and a coastal region of Netherlands to represent the transporting distance between the capture site and target location. Dutch region is hosting several CCUS projects which can potentially receive CO_2 from North of France. Both versions of Tool 1 were used to analyze offshore pipeline (from Northern France to Netherlands) and shipping transport (from Northern France to Netherlands) for this option and the results were compared with each other to identify the cost optimal transport method.

The following inputs were used in Tool 1 (2012)[22]:

- <u>Offshore pipeline</u>
  - Transport rate: 1 MTPA
  - Project lifetime 15 years
  - Pipe length: 200 km
  - Optimum pipeline diameter: 10.75-inch OD
  - Inlet pressure: 110 bar
  - Outlet pressure: 80 bar
  - Cost of steel: 1800 €/ton
  - Real discount rate: 7 %

[21] For assessment for MP transport some parameters had to be manipulated in Tool 1 (2017) using parameters from Tool 2 .
[22] All ship transport pressures are at 7 bara (LP)

- Shipping between harbors
  - Transport rate: 1 MTPA
  - Project lifetime: 15 years
  - Ship size: 21825 m^3
  - Number of ships: 2
  - Shipping distance: 200 km
  - Ship speed: 26 km/hour
  - Real discount rate: 7 %
  - Ship utilization rate: 85 %

The following inputs were used in Tool 1 (2017):

- Offshore pipeline
  - Transport rate: 1 MTPA
  - Project lifetime 15 years
  - Pipe length: 200 km
  - Optimum pipeline diameter: 10.75-inch OD
  - Inlet pressure: 110 bar
  - Outlet pressure: 80 bar
  - Cost of steel: 1800 €/ton
  - Real discount rate: 7 %

- Shipping between harbors
  - Transport rate: 1 MTPA
  - Project lifetime: 15 years
  - Ship size: 4800 m^3
  - Number of ships: 2
  - Shipping distance: 200 km
  - Ship speed: 26 km/hour
  - Real discount rate: 7 %
  - Ship utilization rate: 85 %

4.4 Results & Discussion

4.4.1 Analysis results of three alternatives of business case using Tool 1 (2012) and Tool 2 (2018)

4.4.1.1 *Alternative #1: Stand-alone study – Offshore pipeline vs direct shipping (LP)*

Figure 7 shows results of stand-alone study for CO_2 transport by ship and offshore pipeline, with varying distance and flow rate. These results were obtained by using Tool 1 (2012). The CAPEX shown in the graph combines the CAPEX of conditioning and transport part of the chain. When the shipping and offshore pipeline results were combined into a single graph, compared to the pipeline, the ship CAPEX with distance did not seem to have a significant change due to the same number of ships being used to transport over longer distances and shorter distances There is an almost linear increase in pipeline CAPEX to length. The pipeline CAPEX is a function of length and diameter of pipe as well as aggregated pipeline cost (71065 €/inch/km) and riser cost at the field hub. It is obvious that when the pipeline length increases, more material for construction would be required as well as more labor.

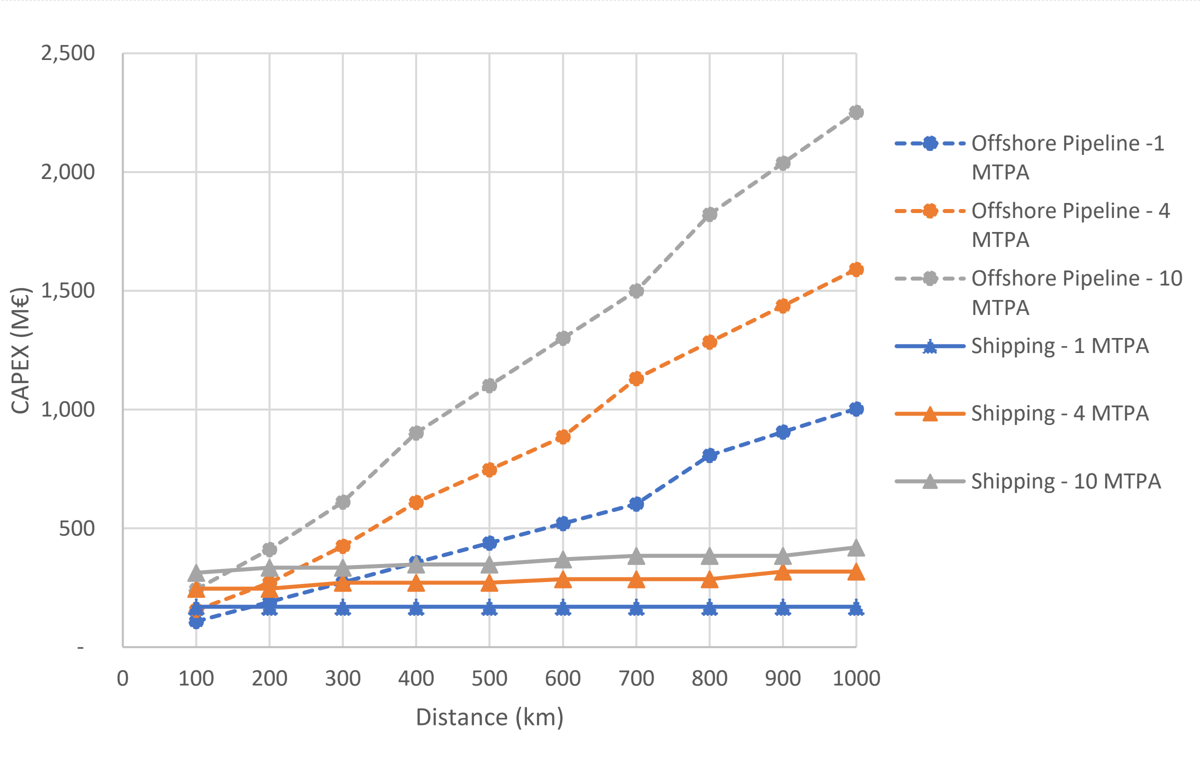


Figure 7: Cost of CO_2 conditioning and transport for varying capacity from Tool 1 (2012)

Figure 7 shows the CAPEX of offshore pipeline with distance is not a straight line and that is because of optimization of pipeline diameter and inlet pressures at each distance. The inlet pressure to the pipeline was changed to optimize the cost of pipeline. For CAPEX line of direct shipping, towards higher distances, the line slopes upwards slightly due to increase in number of ships.

$$CAPEX = D_{EXT} L_c \left(1 + \frac{terrain\ over\ cost\ \%}{100}\right) \frac{Pipeline\ CAPEX\ .\ Pipeline\ overnight\ factor}{10^6} + Reference\ riser\ cost \left(\frac{Transport\ capacity}{Reference\ riser\ capacity}\right)^{0.5}$$

Offshore pipeline with smaller capacities shows a lower CAPEX than pipe with large flow rates. The main contributor to CAPEX in such case is the conditioning CAPEX and pipeline CAPEX. The conditioning costs increases with flow rate, and with the target pressure needed after conditioning. Pipeline with large capacities require large conditioning equipment and more material for construction and therefore they would have a CAPEX.

From Figure 7, it can also be noted that CAPEX difference is significant in offshore pipeline for different flow rates than in shipping transport. The reason for that lies within the conditioning of CO_2 before the export via pipe or ship. For ship export, the CO_2 needs to be conditioned and pressure needs to increase from 1 bara (pressure of captured CO_2) to 7 bara (ship transport pressure). This process will require smaller equipment and therefore lower costs of conditioning. For pipeline export, the CO_2 pressure needs to be pumped to 150 bar from 1 bar, as a result, large conditioning equipment is required with thicker walls and therefore increases the cost significantly.

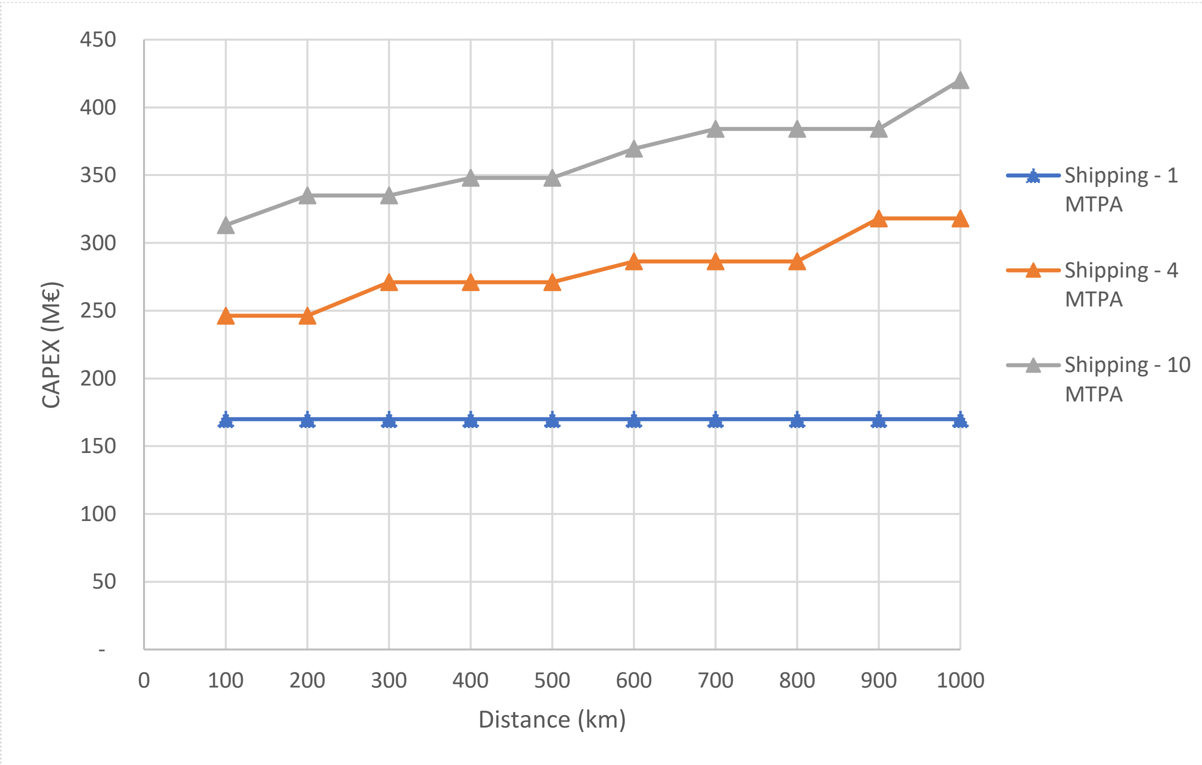


Figure 8: CAPEX of CO_2 transport (incl. conditioning) for varying capacities by ship from Tool 1 (2012)

Figure 8 shows the change in CAPEX of CO_2 transport at different distances and capacities by ship. For a capacity of 1 MTPA, the line is straight due to the possibility of using a single ship of the same size throughout the different distances (this is the cost optimal solution suggested by Tool 1 (2012)). For a capacity of 4 MTPA, there are step changes between 200 and 300 kilometers, 500 and 600 km, and 800 and 900 km. These changes correspond to change in sizes of ship and number of ships being used for transport. At 200 km, a single ship of 21825 m^3 is used while at 300 km a single ship of 30555 m^3 size is used. From 500 km to 600 km, a single ship of 30555 m^3 is used and then 2 ships of 21825 m^3 is cost optimal. Table 5 corresponds to number of ships and sizes of ships being used to transport 4 MTPA.

Table 5: Ship size and number of ships in Tool 1 (2012) used to transport 4 MTPA of CO_2

Ship size (m^3)	Number of ships
21825	1
21825	1
30555	1
30555	1
30555	1
21825	2
21825	2
21825	2
30555	2
30555	2

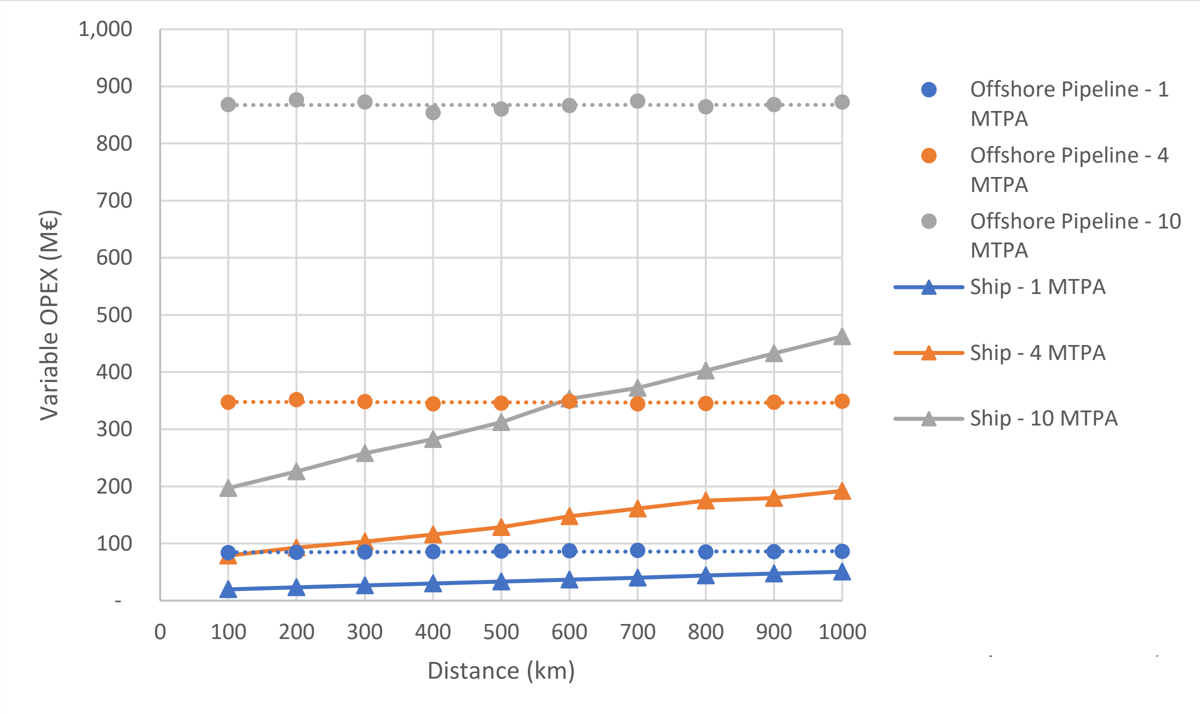


Figure 9: Variable OPEX for CO_2 transport (incl. conditioning) for varying capacities by pipe or ship from Tool 1 (2012)

Figure 9 shows a constant variable OPEX for offshore pipeline case because the transport of CO_2 through pipeline does not consume any fuel or electricity and thus it does not have variable OPEX. The main contribution is solely from conditioning of CO_2. The greater the amount of CO_2 captured, the higher the conditioning costs and higher the variable OPEX (depending on electricity consumption and cooling water consumption). The linear trend of variable OPEX with distance for CO_2 transport by ship is caused by the increase in fuel cost. Large amount of CO_2 transported requires larger ships and several number of ships which results in increase in fuel cost.

Figure 10 shows total discounted costs of pipeline transport compared to ship transport for varying capacities and distance, where the offshore pipeline shows a linear increase in total costs as pipe length increases from 100 km to 1000 km. Increase in total costs for ship transport is at a slower rate than increase in total costs for pipeline.

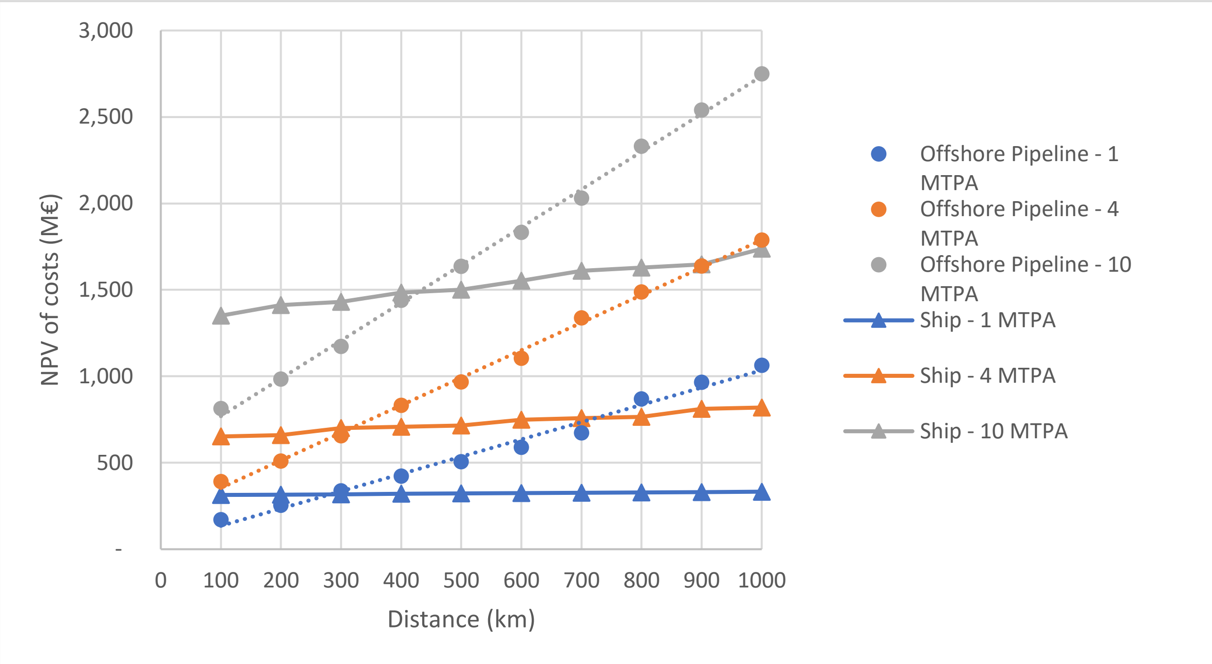


Figure 10: Total discounted costs for CO_2 transport (incl. conditioning) for varying capacities from Tool 1 (2012)

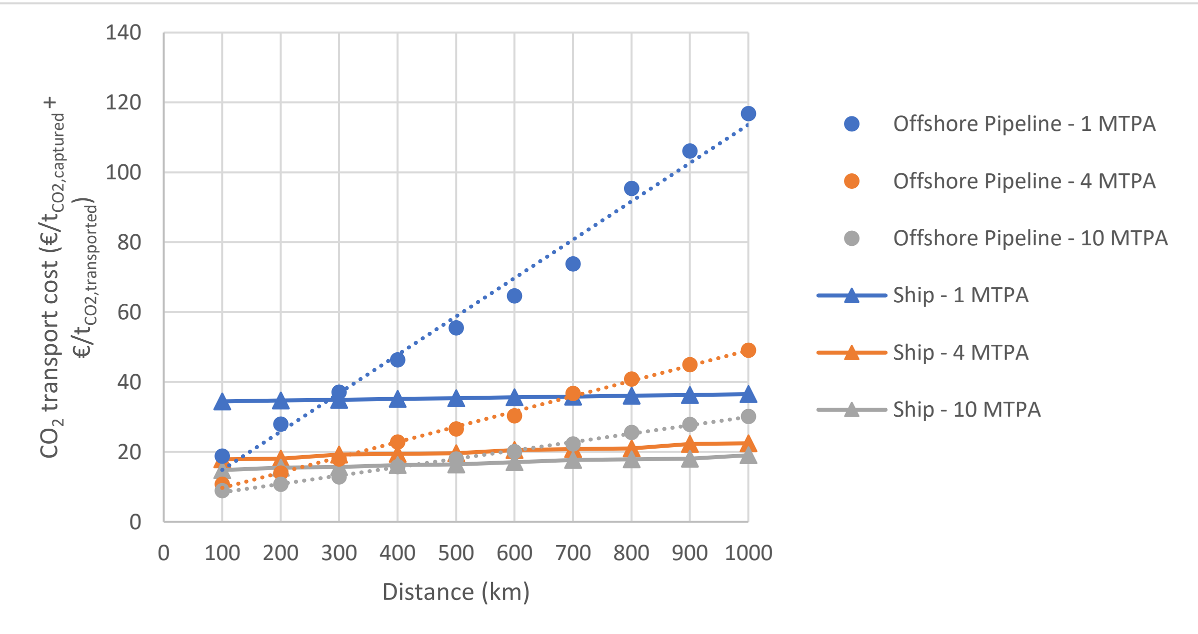


Figure 11: CO_2 transport cost (incl. conditioning) for varying capacities from Tool 1 (2012)

Figure 11Figure 11 illustrates the CO_2 transport cost in € per $t_{CO2,transported}$ which depends on the net present value (NPV) of costs and discounted volume. NPV is calculated as sum of discounted cash flow that adds all the CAPEX and OPEX while considering the real discount rate. CO_2 transport cost is lower for larger flow rates. Figure 11 can be used to identify low cost option for transport based on the transport distance. If 1 MTPA is being transported, for distances below 300 km offshore pipeline is a cheaper option and above 300 km it is better to use ship transport. For transporting 4 MTPA, distances below 310 km should use offshore pipeline while greater than 310 km should use ship transport. For transporting 10 MTPA, distances below 400 km should use offshore pipeline while greater than 400 km should use ship transport.

Figure 12 shows that for low transport volume, CO_2 transport through offshore pipeline emits less Greenhouse gas (GHG) than ship and as the distance increases the difference between GHG emissions from both transport options approaches zero. For medium transport volume (e.g. 4 MTPA) the difference in GHG emissions between offshore pipeline transport and direct shipping is about 1 million tonne of CO_2 where shipping releases higher emissions than pipeline. At high flow rates of 10 MTPA and above, the difference between GHG emissions from the two transport options is between 2 million tonne to 3 million tonne of CO_2. The main reason for shipping transport releasing more GHG than pipeline is due to the heavy fuel oil consumption by ships and conditioning unit.

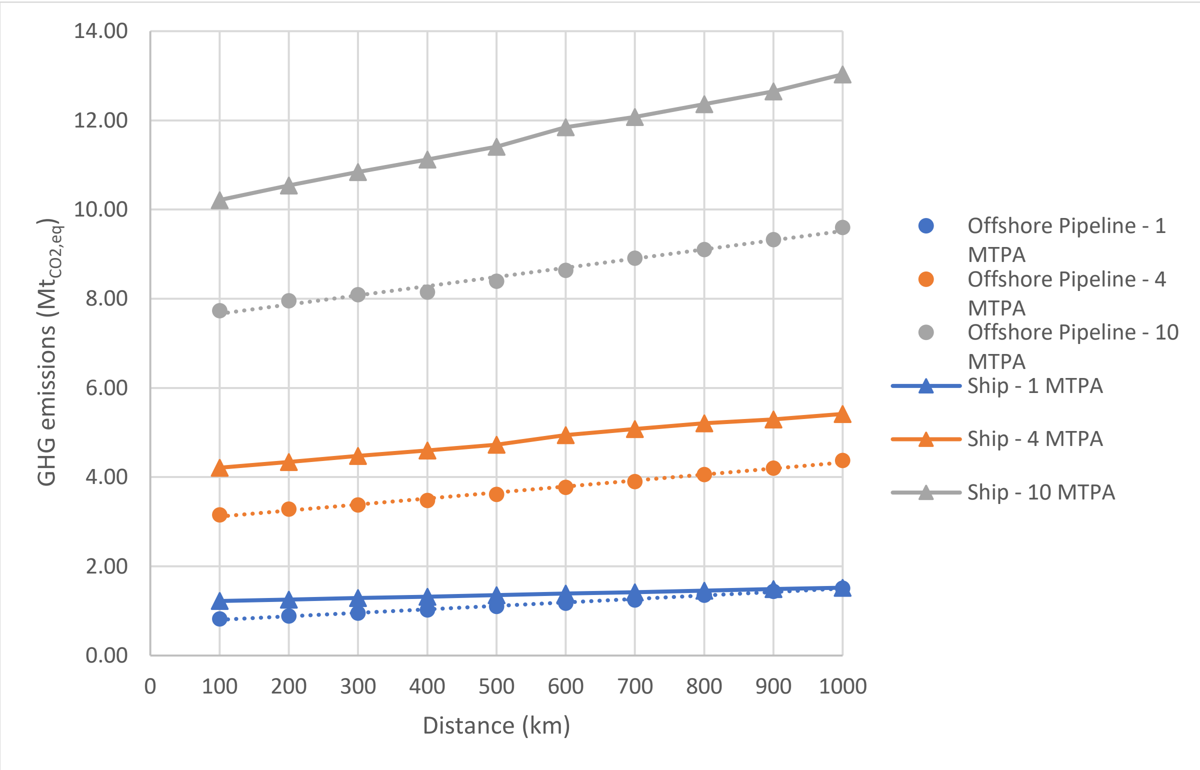


Figure 12: GHG emissions for CO_2 transport (incl. conditioning) for varying capacities from Tool 1 (2012)

Figure 13 shows a linear relationship between the distance and the fuel consumption for the overall transport process by ship which is an important parameter to determine fuel cost. Linear trend of fuel consumption also means that the fuel cost for these flow rates will be linear and will follow a similar pattern to Figure 13. Amount of fuel consumed by ship CO_2 transport depends on the number of ships used, the size of each ship and the speed the ship is travelling at. Larger ships, higher number of ships or ships travelling at higher speeds will consume more amount of fuel compared to smaller, a smaller number of ships or slow speed of travel. From Figure 13, it shows that to transport 1 MTPA, a single ship of size 21825 m^3 must have been used throughout the distance from 100-1000 km. In this case the fuel consumption only depended on the distance travelled. For flow rates of 4 and 10 MTPA the steeper liner is due to changes in ship size (cost optimal ship size is given by Tool 1 (2012)) and the number of ships required to transport CO_2 to a certain distance.

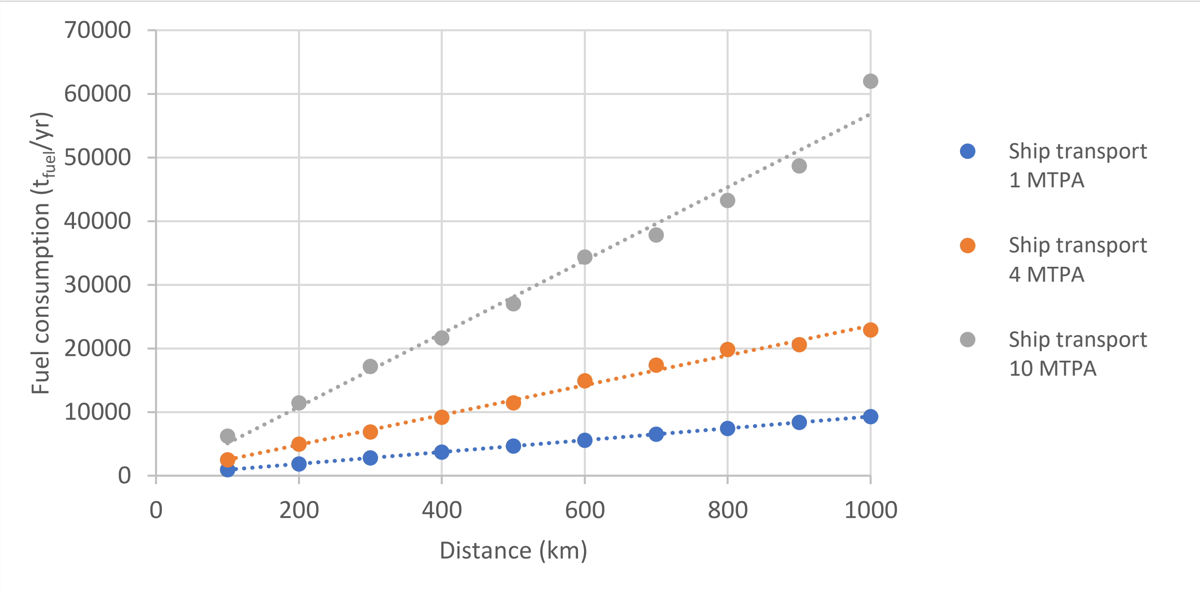


Figure 13: Fuel consumption by ship with varying travel distance (obtained from Tool 1 (2012))

When the stand-alone concept was re-simulated in Tool 1 (2017), some differences were seen in CAPEX and OPEX calculated by the tool. Figure 14 shows the total discounted costs of offshore pipeline transport of 1 MTPA of CO_2 (including conditioning CAPEX) calculated by both versions of Tool 1. It can be seen that Tool 1 (2012) gives a lower total cost than Tool 1 (2017) at all distances, however as distance between capture site and storage site increases, the costs difference from the two tools increases (from 26 to 310 M€). Tool 1 (2017) shows higher costs due to an updated pipeline cost model used in the tool instead of an aggregated CAPEX used in Tool 1 (2012). The updated pipeline cost model considers the labor cost, ROW and miscellaneous cost as a function of pipeline dimensions.

Figure 15 shows the difference in total discounted costs of CO_2 transport via offshore pipeline when the flow rate is 10 MTPA. Tool 1 (2012) still shows a lower cost than Tool 1 (2017), however the difference in total costs results between the two tools significantly increases as the distance increases. From 100 km to 1000 km, the cost differences between Tool 1 (2012) and Tool 1 (2017) for transporting 10 MTPA of CO_2 increases from 60 to 1400 M€. The reason for such a large difference is the same that Tool 1 (2017) uses an updated version of pipeline cost model that considers several factors, and as flow rate increases these factors impact the costs resulting in a large difference.

When direct shipping cost results were assessed by both versions of Tool 1, the results were different compared to offshore pipeline transport. For low flow rate of CO_2 (e.g. 1 MTPA), Tool 1 (2012) showed a higher total discounted cost than Tool 1 (2017). This can be seen in Figure 16. The main reason for that is Tool 1 (2012) has only three ship sizes available for the user to select (21825, 30555 and 39285 m^3). When 21825 m^3 of ship is used to transport 1 MTPA, the ship would either be half empty in each of its journey or it would finish transporting 1 MTPA in the middle of the year if it was to transport up to full capacity. On the other hand, Tool 1 (2017) allows user to select ships of smaller sizes to transport 1 MTPA ensuring that full capacity of ship is used throughout each cycle and therefore lowers the transport CAPEX and OPEX significantly.

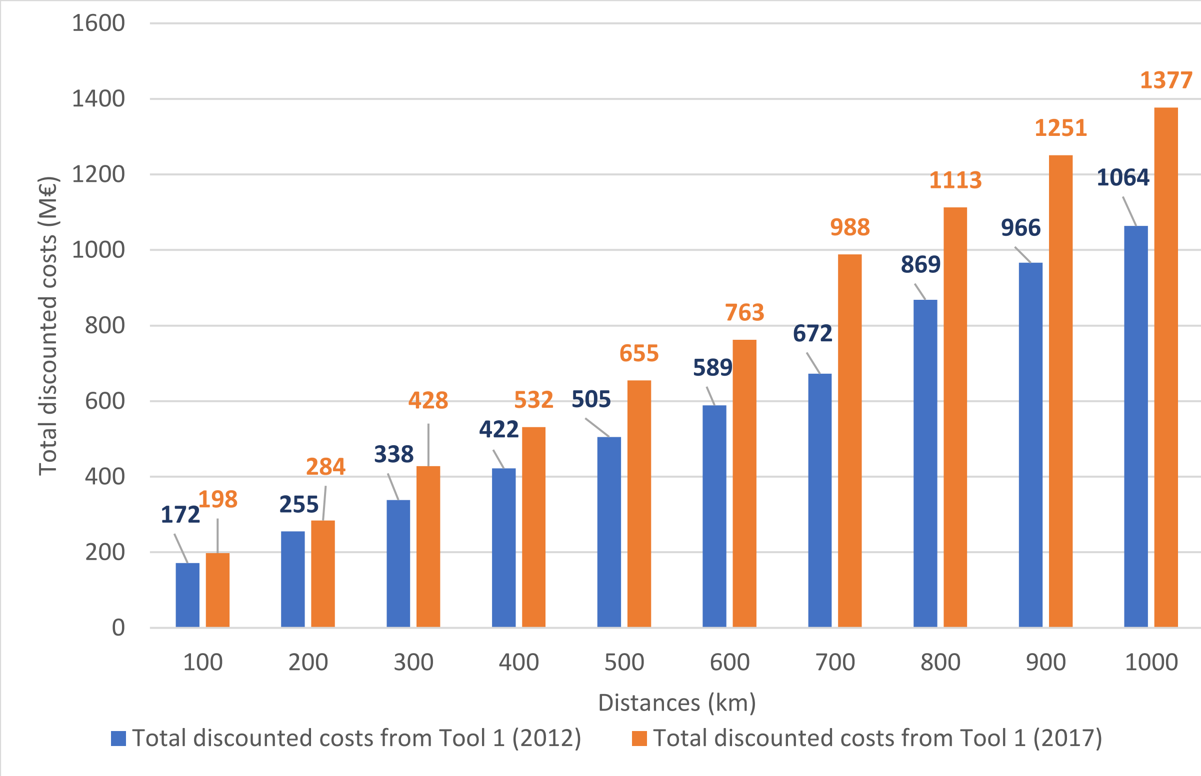


Figure 14: Comparison of total discounted costs of 1 MTPA (Alternative #1 of business case) for offshore pipeline from Tool 1 (2012) and Tool 1 (2017)

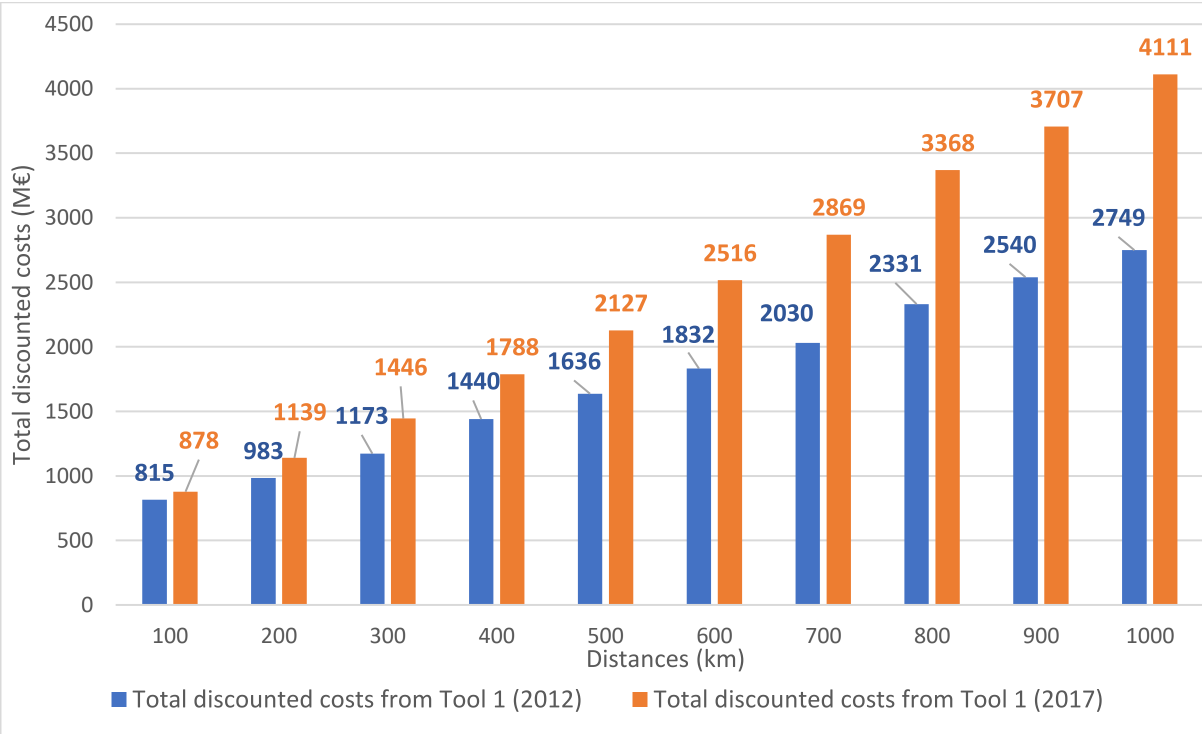


Figure 15: Comparison of total discounted costs of 10 MTPA (Alternative #1 of business case) for offshore pipeline from Tool 1 (2012) and Tool 1 (2017)

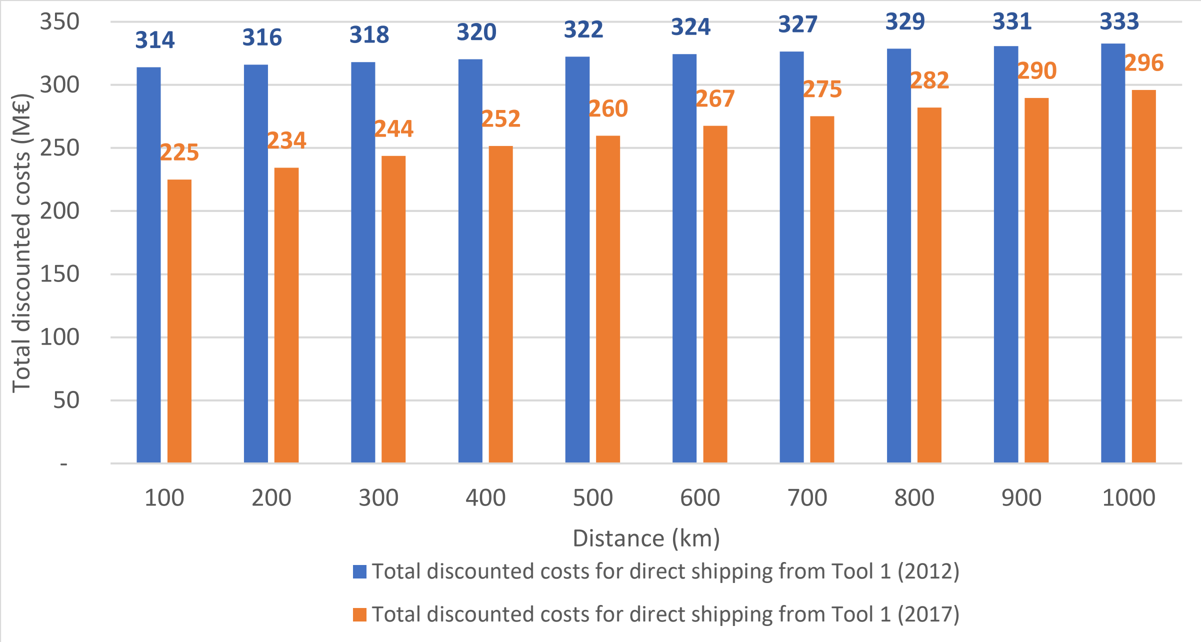


Figure 16: Total discounted costs of 1 MTPA (Alternative #1 of business case) for direct shipping from Tool 1 (2012) and Tool 1 (2017)

Figure 17: Total discounted costs of 10 MTPA (Alternative 1 of business case) for direct shipping from Tool 1 (2012) and Tool 1 (2017)

At large flow rates of CO_2 (e.g. 10 MTPA), the difference in total discounted costs between the two tools are within ±50 M€. This can be seen in Figure 17. In short, at high flowrates the total costs of direct shipping given by the two version of Tool 1 are almost similar and the differences can be neglected since they only account for less than 5 % of costs. The reason that Tool 1 (2017) showed similar total costs for direct shipping as Tool 1 (2012) is because of large sizes of ships needed to transport 10 MTPA.

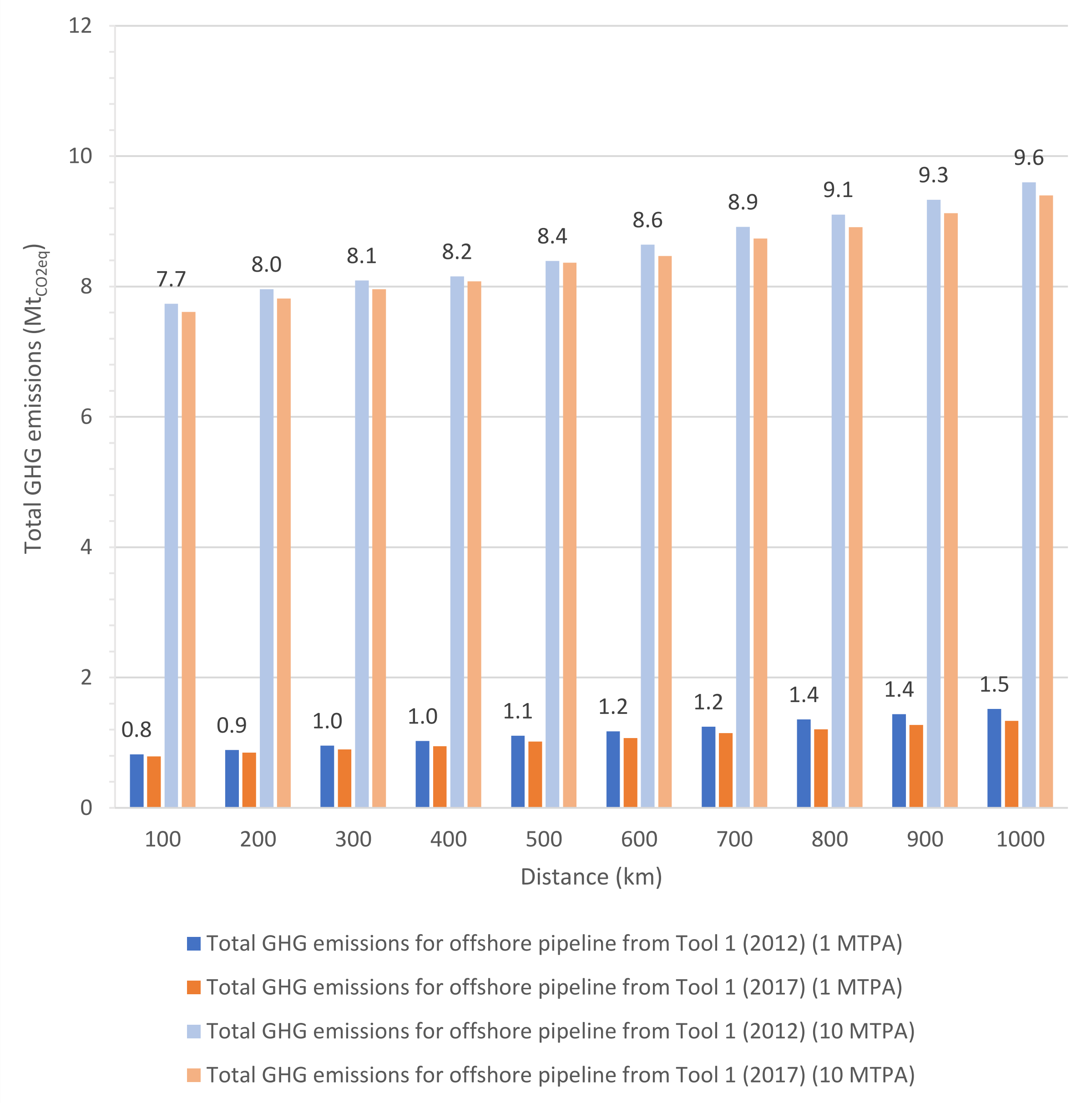


Figure 18: Comparison of total GHG emissions for offshore pipeline with 1 MTPA and 10 MTPA obtained from Tool 1 (2012) and Tool 1 (2017)

Moving on from cost assessment, carbon footprint assessment results for offshore pipeline and direct shipping were also obtained from both versions of Tool 1. Figure 18 shows GHG emissions from offshore pipeline transport (including conditioning) for 1 MTPA and 10 MTPA using both tools. At low flow rate of CO_2, it can be seen that Tool 1 (2012) gives slightly higher emission than Tool 1 (2017). The same can be said for 10 MTPA of CO_2. The reason for Tool 1 (2012) showing higher emissions is due to outdated climate impact factors (Global Warming Potential factors) used in the tool. Tool 1 (2017) have climate impact factors updated to 2016 levels and therefore shows a lower emission than previous version of the tool.

4.4.1.2 *Alternative #2A: Plug-in NCS, Norway – Offshore pipeline vs direct shipping (LP) and Shipping transport (MP vs LP)*

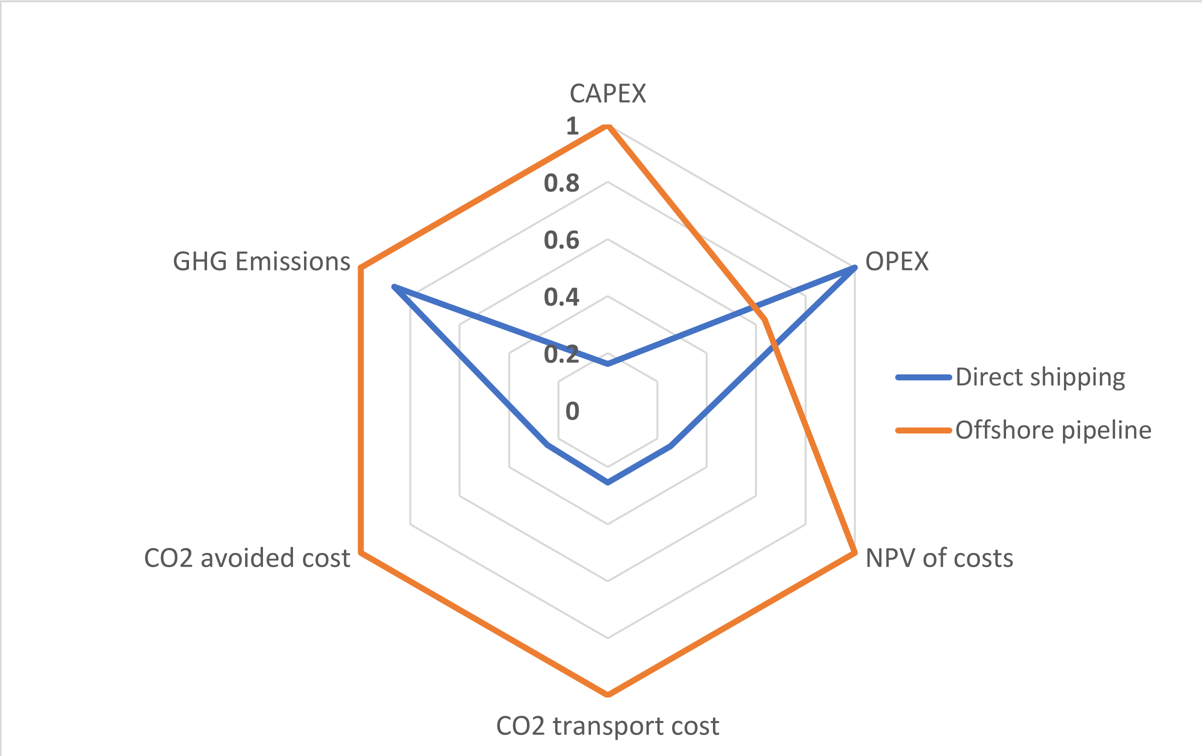


Figure 19: Results of multicriteria analysis in Tool 1 (2012) of offshore pipeline and direct shipping transport (LP) to a project connected to NCS, Norway (Alternative #2A of business case)

Figure 19 shows a radar chart that is used to compare key performance indicators (KPI) of offshore pipeline with KPI of direct shipping. It can be interpreted as the following; direct shipping CAPEX is around 20 % of CAPEX of offshore pipeline. CO_2 avoided costs, CO_2 transport costs and NPV of costs for direct shipping are all 25 % of KPIs of offshore pipeline. OPEX which includes maintenance, labor, insurance and variable utilities required for transport is higher for direct shipping than for offshore pipeline transport (offshore pipe OPEX is around 65 % of OPEX of direct shipping). GHG emissions from the construction and operation of shipping export is 90 % of GHG emissions from pipeline transport. Overall according to Figure 19, in order to transport and store CO_2 from North of France to a location in the NCS, direct shipping is a more economical option compared to pipeline. The possible reason for that could be that the distance between Northern France and the storage location is greater than 1000 km, and at large distances the pipe material costs, labor costs and miscellaneous costs are significantly higher compared to having a few ships transporting CO_2 back and forth.

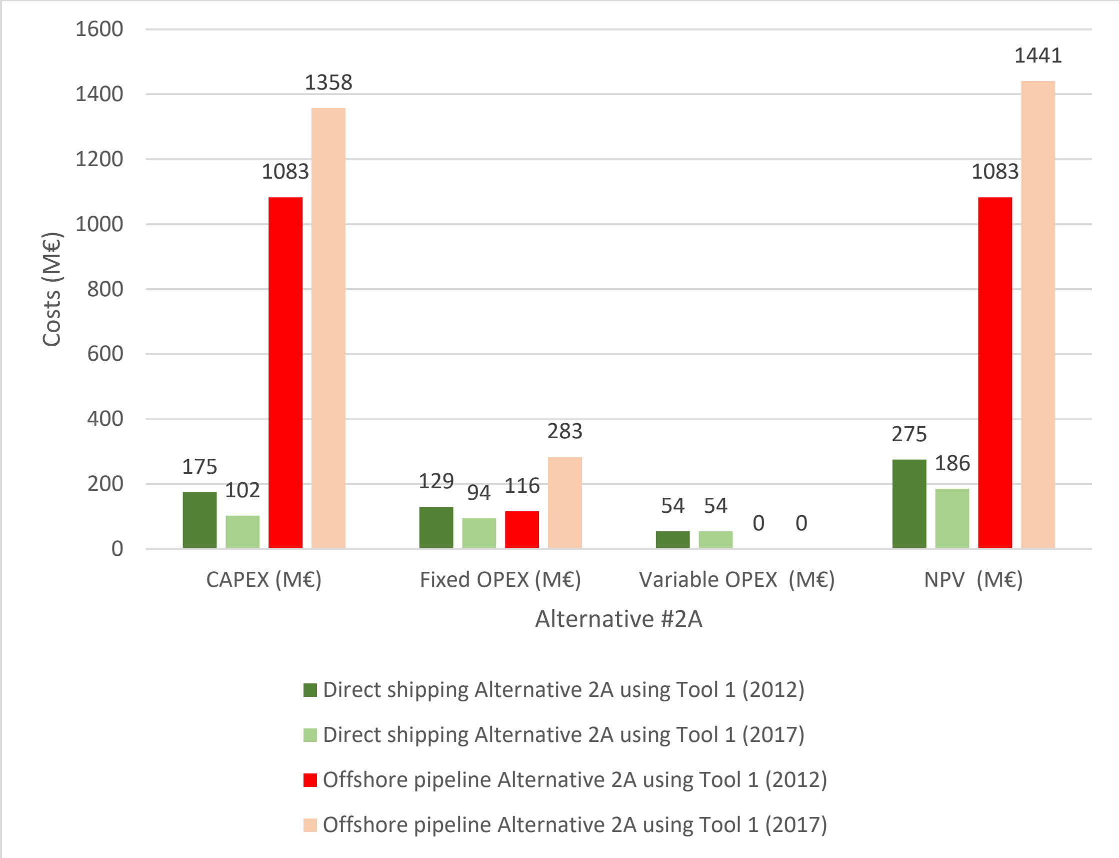


Figure 20: Comparison of Alternative #2A cost results from Tool 1 (2012) and Tool 1 (2017)

The breakdown of cost components for alternative #2A that make up the total discounted lifetime costs can be seen in Figure 20. In direct shipping scenario, Tool 1 (2012) gives slightly higher costs than Tool 1 (2017), however the biggest difference in costs can be seen in offshore pipeline scenario between the two versions of the tool. Tool 1 (2012) gives lowers investment costs and therefore the total discounted costs of offshore pipeline given by Tool 1 (2012) is almost 300 M€ lower than what is given in Tool 1 (2017). The large difference in pipeline costs comes from updated pipeline cost methodology used in Tool 1 (2017) compared to Tool 1 (2012). Another point to note here is that Tool 1 (2012) used two ships of 21825 m^3 size for direct shipping while Tool 1 (2017) used two ships of 7500 m^3 size. This explains why Tool 1 (2012) gave higher CAPEX and OPEX for direct shipping compared to Tool 1 (2017).

If CO_2 from North of France is transported to a hub in Western Coast of Norway via ship between harbor scenario, results from Tool 2 in Figure 21 shows that low pressure transport option is economical compared to medium pressure. The total costs of transport for each option in Figure 21 shows the dominating component of costs are liquefaction fuel cost, ship CAPEX and ship OPEX. Costs of liquefaction decreases when transport pressure is increased from 7 bara to 15 bara due to lower energy required for refrigeration in the latter. MP transport also leads to higher ship costs due to ships requiring storage and facilities that would need thick walls to hold CO_2 at 15 bara. The detailed costs from Tool 2 can be found in Table 18 and Table 19 on page 83 and 84.

A point to note for MP transport is that there is a size restriction on the ships due to the maximum diameter the tanks can have for a specific design pressure. The largest ship available for MP ship transport of CO_2 is 10000 m^3. However, Tool 2 uses a ship size of 20000 m^3 (can be seen in Table 18 and Table 19) which currently does not exist but maybe in the future might be a possibility.

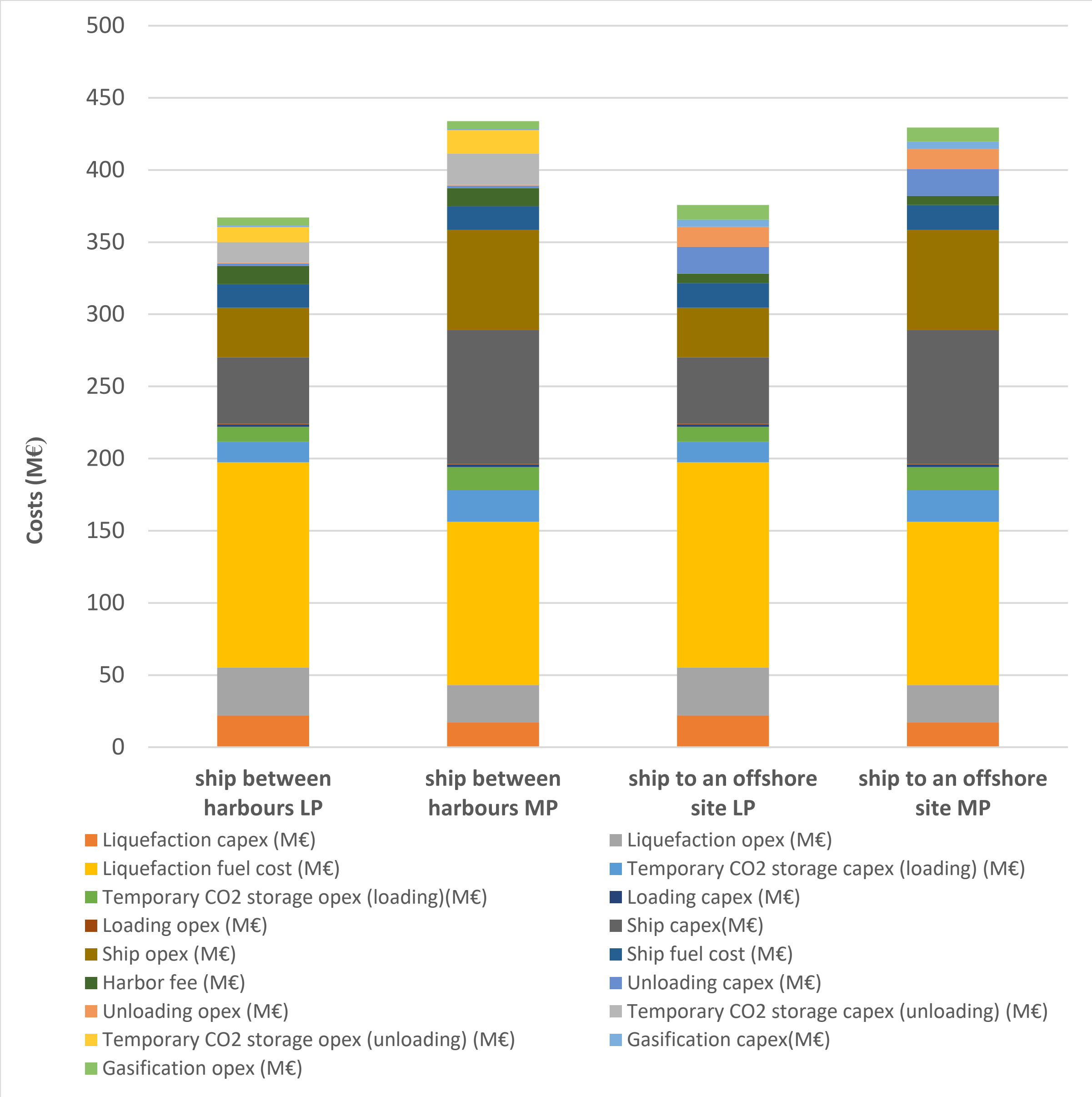


Figure 21: Alternative #2A analysis results from Tool 2 for shipping transport (MP vs LP)

Although LP transport is more economical than MP transport according to Tool 2 results, the GHG emissions released by construction and operation of CO_2 transport system is higher for LP transport mainly due to liquefaction (conditioning) unit. LP system requires more energy for the refrigeration part of liquefaction unit and hence more electricity is consumed which release 25 % higher amount of CO_2 (because the tool uses electricity generation from natural gas) compared to MP liquefaction system. From Figure 22 it can be seen that the shipping to an offshore site releases 5 % more emissions compared to shipping between harbors which could be due to fuel consumption and construction of unloading facilities at storage site.

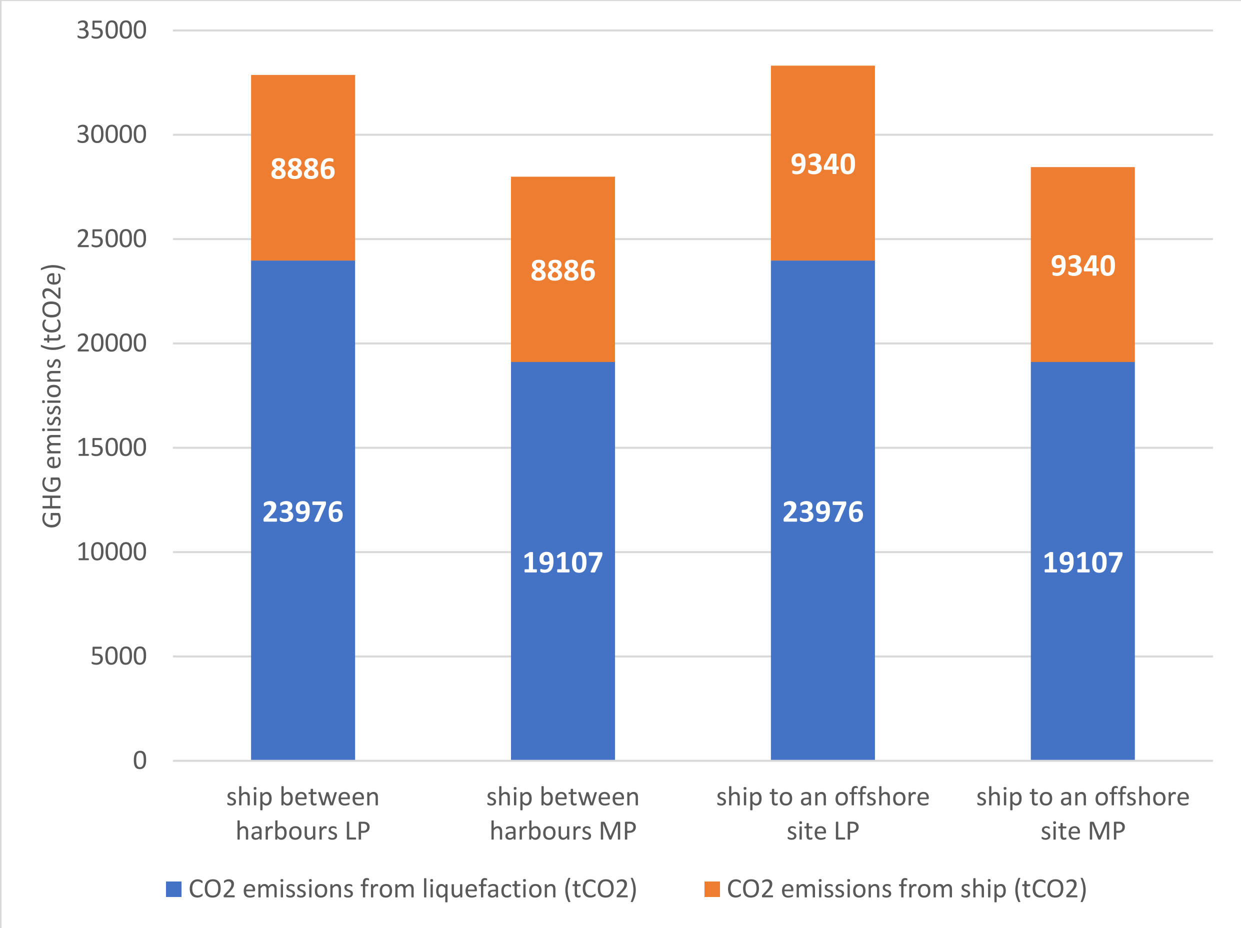


Figure 22: GHG emissions for MP vs LP shipping transport options using Tool 2 (Alternative #2A)

4.4.1.3 *Alternative #2B: Project connected to NCS - Shipping between harbors (MP vs LP)*

The simulations for alternative #2B of the business case was ran in Tool 2 and Tool 1 (2017) to obtain results for shipping between harbors. These data are presented in Table 6 for LP transport. The results from both of the simulation tools were compared to each other.

Conditioning CAPEX is almost two times higher given by Tool 1 (2017) compared to Tool 2 according to Table 6. A possible reason for such difference in conditioning costs is that Tool 2 uses conditioning costs summarized from several literature while Tool 1 (2017) uses a combination of ASPEN Process Economic Analyzer software and literature. Conditioning variable OPEX of 8.44 M€ per year was given by Tool 1 (2017) which was about 15 % lower than variable OPEX from Tool 2 due to the tool calculating higher electrical consumption by the conditioning unit than Tool 1 (2017).

Storage and loading CAPEX from Tool 1 (2017) for shipping between harbors is 13 M€ which is almost two times higher than CAPEX calculated by Tool 2. The reason is Tool 1 (2017) assumes storage size is 25 % larger than the ship size and assumes a larger unitary storage CAPEX of 1038 $€_{2016}/m^3$, while Tool 2 has assumed storage size to be 20 % greater than ship size and storage unitary CAPEX as 455 $€/m^3$. As stated in Table 6, ship CAPEX from Tool 1 (2017) is reported as around 41 M€ (20.5 M€ per ship of size 7500 t_{CO2}) whilst Tool 2 shows that ship CAPEX is 57 M€ (each ship of size 8000 t_{CO2} costs 28.4 M€). The reason for Tool 1 (2017) showing a lower ship CAPEX is that it uses 'Nth-of-a-kind' (NOK) cost methodology for the technology which assumes the technology is matured and hence CAPEX of ships is low. Tool 2 gives a higher ship CAPEX due to regression analyses of several ship CAPEX data from literature which was a mix of NOK and 'First-of-a-kind' (FOK) cost data.

Table 6: Comparison of results for LP shipping between harbors (Alternative #2B) using Tool 2 and Tool 1 (2017)

Low Pressure shipping between harbors	Tool 1 (2017)	Tool 2 (2018)
Conditioning CAPEX (M€)	41.32	23.08
conditioning fixed OPEX (M€/y)	2.27	2.31
Conditioning variable OPEX (M€/y)	8.44	9.89
Temporary CO_2 storage & loading CAPEX (M€)	13.08	7.51
Temporary CO_2 storage & loading OPEX (M€/year)	0.59	0.34
Ship CAPEX (M€)	40.66	56.82
Ship OPEX (M€/y)	2.78	2.84
Ship fuel cost (M€/y)	2.32	3.98
Harbor fees (M€/y)	2.18	2.75
Storage and unloading CAPEX (M€)	13.08	7.51
Storage and unloading OPEX (M€/year)	0.59	0.34
Reconditioning CAPEX (M€)	1.95	0.99
Reconditioning OPEX (M€/y)	0.47	0.39
NPV of costs or Total discounted lifetime costs (M€)	319	421
CO_2 Transport cost (€/$t_{co2,transported}$)	29.9	39.4

Ship fuel cost presented in Tool 2 for this simulation came out to be almost double of fuel cost from Tool 1 (2017). A possible explanation of that is Tool 2 uses LNG as fuel for the ships and assumes a greater number of trips per ship compared to Tool 1, as well as Tool 2 uses a slightly larger ship size based on availability (8000 t_{CO2}) resulting in more fuel consumption and fuel cost. For storage and unloading CAPEX, the reason for Tool 1 (2017) showing almost twice the result from Tool 2 is the same as for storage and loading mentioned earlier.

Overall the total discounted lifetime costs (seen in Table 6) from Tool 2 were about 100 M€ higher than Tool 1 (2017). Tool 1 (2012) showed a low lifetime costs mainly due to NOK cost methodology that results in lower investment costs for technology which will happen sometime in the future. Currently CCS is not yet commercialized and matured so the investments costs are higher than what is used in Tool 1 (2012). It cannot be said which tool gives accurate results since the results obtained from these tools have not been compared to successful CCS projects. These tools are made based on studies performed by various CCS organization, CCS experts and companies.

Similarly to LP ship transport, costs for MP transport from simulations in the studied tools were compared and are presented in more details on page 86 and 93.

4.4.1.4 *Alternative #3: plug-in project in Netherlands – Offshore pipeline vs shipping between harbors (LP)*

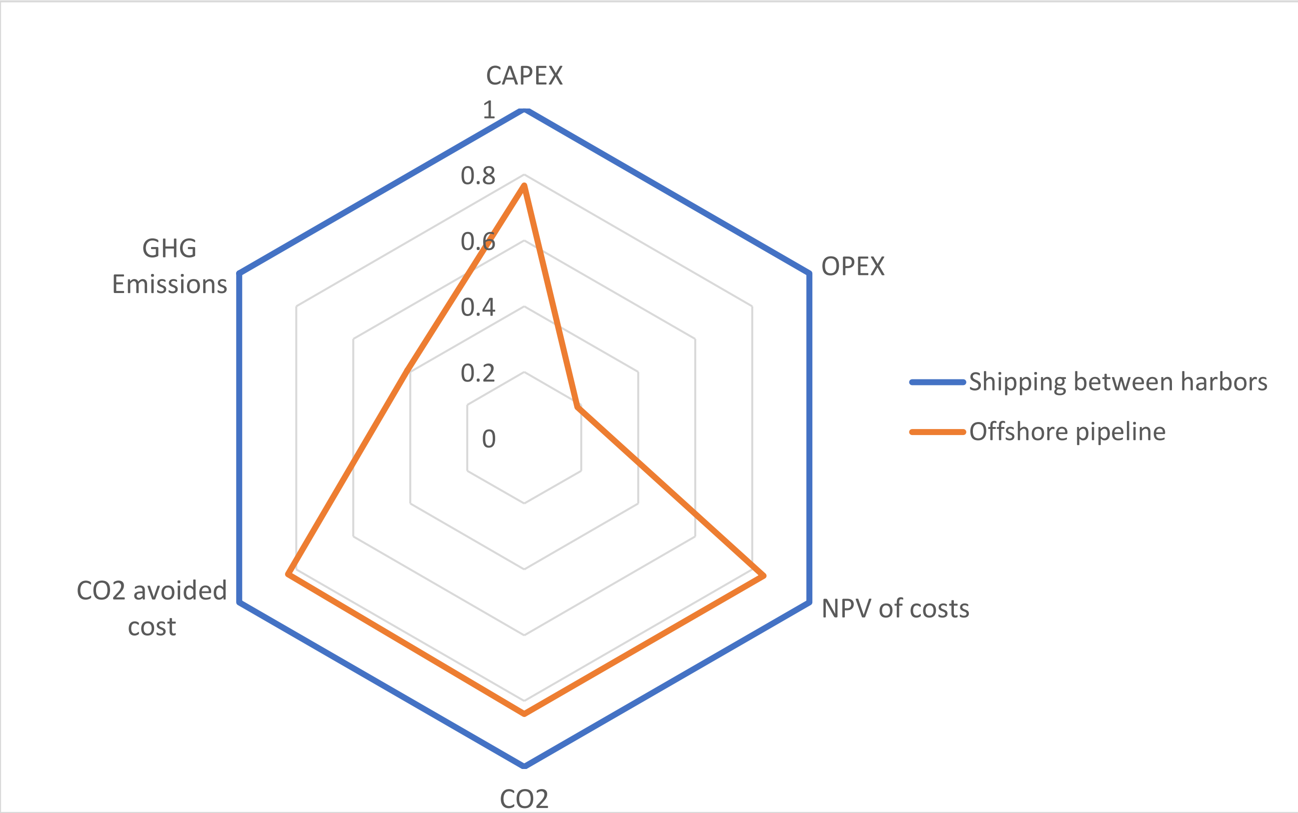


Figure 23: Results of multicriteria analysis in Tool 1 (2012) of pipeline and shipping offshore transport (LP) to Netherlands

Figure 23 shows a radar chart to compare KPI of offshore pipeline with KPI of shipping between harbors for third alternative of the business case. It can be interpreted as the following; offshore pipeline CAPEX is around 80 % of CAPEX of shipping between harbors. CO_2 avoided costs, CO_2 transport costs and NPV (net present value) of costs for offshore pipeline are all around 85 % of these KPIs of shipping between harbors. OPEX which includes maintenance, labor, insurance and variable utilities required for conditioning is higher for shipping between harbors than for offshore pipeline transport (offshore pipe OPEX is around 20 % of OPEX of shipping). GHG emissions from the construction and operation of pipeline export is 40 % of GHG emissions from shipping between harbors. Overall according to Figure 23, in order to transport and store CO_2 from north of France to Netherlands, offshore pipeline export is a more economical option compared to shipping between ports. The possible reason for that is that the distance between Northern France and the storage location is about 200 km, and at short distances the pipe material costs, labor costs and miscellaneous costs are significantly lower compared to costs of having a few ships transporting CO_2 back and forth.

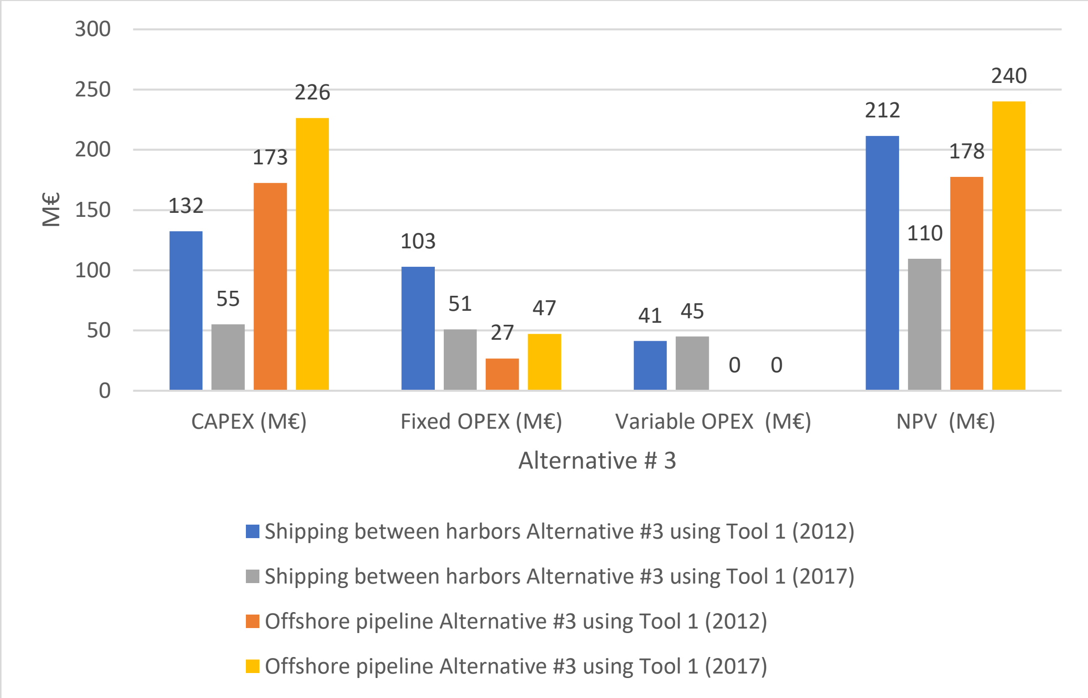


Figure 24: Comparison of Alternative #3 cost results from Tool 1 (2012) and Tool 1 (2017)

When the cost results from both versions of Tool 1 were compared (refer to Figure 24), the largest difference in costs were seen for shipping between harbors scenario. Tool 1 (2012) used two ships of 21825 m^3 while Tool 1 (2017) used two ships of 4800 m^3 size, which explains the reason why CAPEX and OPEX of shipping between harbors in earlier version of Tool 1 is higher than the latest version. Tool 1 (2017) has many more ship sizes available for user to select making it easier for user to optimize the use of ship and reduce costs of shipping transport. Similar to Figure 20, in Figure 24 offshore pipeline costs from Tool 1 (2012) are lower than pipeline costs from Tool 1 (2017) for the same reason of updated pipeline cost model being used in the latter.

4.5 Key findings from Chapter 4

4.5.1 Pipeline vs Shipping

In general:

- When comparing direct shipping to offshore pipeline, as the distance between source of CO_2 capture and storage location increases, there is a linear increase in pipeline CAPEX whilst the CAPEX of shipping transport changes very little over the 1000 km distance due to the same number of ships being used to transport CO_2.
- Low flow rates of CO_2 transport result in low offshore pipeline CAPEX due to small diameters of pipeline. As pipeline length increases to match distance between capture site and storage site, the pipeline diameter needs to be larger to match the appropriate pressure drop, resulting in steep increase in CAPEX with distance.
- High flow rates show high pipeline CAPEX and a steep increase in CAPEX with distance. High flow rates of CO_2 transport require larger pipelines which are costlier than pipeline for low flow rates.
- High flow rates show higher shipping CAPEX compared to smaller flow rates mainly due to size and cost of temporary storage and on-board reconditioning facilities.

- For a flow rate of 1 MTPA of CO_2, at distances below 300 km, offshore pipeline option is more economical compared to direct shipping.
- For higher flow rates such as 10 MTPA, at distance below 450 km, offshore pipeline is more economical. In short, for larger distances, direct shipping is a better option economically compared to offshore pipeline and vice versa.
- CO_2 unit transport cost is higher for low flow rates of CO_2 due to lower abatement potential of the transport system and it is lower for high flow rates due to large amount of CO_2 emissions avoided according to life-cycle assessment of the transport system.
- For high flow rates, direct shipping emits more GHG than pipeline and for small flow rates the difference in GHG emissions between offshore pipeline and direct shipping is negligible.
- For plugging in project connected to NCS (Alternative #2B of business case), it is more economical to choose direct shipping transport option because of lower costs compared to pipeline. This is due to shipping transport being cheaper for large distances than pipeline despite it having similar carbon footprint as pipeline.
- For plugging in project in Netherlands (Alternative #3 of business case), offshore pipeline transport option is more cost-effective than shipping between harbors and also has lower carbon footprint.

4.5.2 MP vs LP Shipping

- According to Tool 2, MP shipping between harbors and MP direct shipping are less economical compared to their LP counterparts, however MP shipping releases lower GHG emissions than LP shipping over the lifetime of the project. This is due to the fact the liquefaction energy requirement is higher in LP than MP.
- If the electricity generated for liquefaction process is coming from renewable sources, then the GHG emissions of LP ship transport can potentially be lower than MP ship transport.
- An important point to note is that there are size restrictions on MP ships up to 10000 m^3. Tool 2 uses MP ships of sizes beyond 10000 m^3 based on theoretical study which might not be feasible in practice.

4.5.3 Comparison of tools

- Tool 1 (2012) shows lower cost results compared to Tool 2 because it assumes a Nth-of-a-kind cost methodology, assuming that the technology is mature, therefore the investment costs are low.
- Tool 1 (2012) shows lower pipeline CAPEX than Tool 1 (2017) due to an outdated pipeline cost model used in the earlier version of Tool 1. This has since been replaced by an improved pipeline cost model resulting in higher pipeline CAPEX given in Tool 1 (2017).
- Tool 1 (2012) shows higher ship CAPEX (and thus higher total shipping costs) than Tool 1 (2017) due to limited ship sizes available in the earlier version of Tool 1. Tool 1 (2017) allows user to select their own ship size which can be sized to optimized shipping costs.
- Carbon footprint evaluation from Tool 1 (2012) gives emissions of transport systems that are slightly higher than emissions calculated by Tool 1 (2017) due to outdated climate impact factors used in the former version of the tool.
- Tool 1 (2012) cannot be used for MP shipping transport assessment due to less flexibility of input parameters.
- Tool 2 gives data for MP and LP transport, however it does not consider size restrictions on MP ships, so the ship size suggested by Tool 2 might not be feasible.

5 Re-use of existing pipeline

5.1 Introduction to Re-using existing pipeline infrastructure business case

Re-using existing infrastructure for CO_2 transport and injection could potentially be a cost-effective option as well as providing environmental benefits. However, it comes with its challenges such as availability and status of infrastructure, limitation with capacity and location of CO_2 sources from the infrastructure etc. Other challenges include the lack of standards in place for reuse of infrastructure and lack of legislation on transport of property/liability.

This business case was studied by Total E&P Norge R&D where the company requested an external environmental consultancy agency and a research organization based in Norway to provide an overview of the potential of reusing Oil and Gas (O&G) infrastructure in the North Sea for CO_2 transport and injection, to quantify the economic and environmental benefits of re-use case as well as identifying the R&D gaps and challenges with re-using infrastructure.

The study investigated two cases, the first one is re-use of 212 km Pipe A case and the second is re-use of 670 km Pipe B.

5.2 Objectives

The objectives of this work can be summarized as follows:

- To map the infrastructure in the North Sea that can be potentially re-used for CO_2 transport and injection.
- To map and evaluate potential CO_2 injection reservoirs in the NCS.
- To define several re-use cases by matching the infrastructure and reservoirs identified above.
- To perform techno-economic and environmental assessments on the identified reuse cases of O&G infrastructure and compare it with new built cases for transport of CO_2.
- To identify and quantify the potential benefits of reusing existing infrastructure compared to new built cases.
- To compare techno-economic and environmental assessment results obtained by both versions of Tool 1.

It should be noted that this study is a pure R&D study with the objective of investigating potential benefits of re-use of existing systems for CO_2 transport and injection. It does not have any objectives of defining real business cases.

5.3 Pipe A Case

5.3.1 Case description

Pipe A is an existing offshore pipeline infrastructure in the North Sea operating since 2003 with 212 km length and 30-inch outer diameter. This pipeline can transport more than 20 MTPA of CO_2 however such quantities of CO_2 are not available in the vicinity of the pipeline. There is a potential of capturing 5 MTPA of CO_2 near entrance of Pipe A with a possibility of receiving CO_2 from other parts of the region to transport at full capacity of pipeline. Pipe A was evaluated through four subcases which are shown in Figure 25. Each subcase was simulated in Tool 1 (2012). Each subcase assumes an onshore storage upstream of pipeline transport.

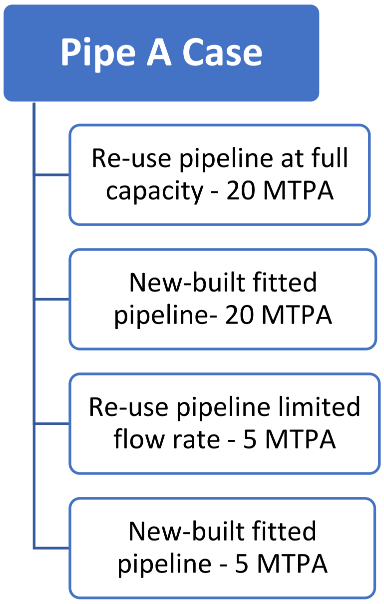


Figure 25: Pipe A subcases

5.3.2 Methods

For each subcase evaluated under Pipe A case, a simple transport system was designed, and the input parameters were set into Tool 1 (2012). The design of the transport system of the subcases of Pipe A are illustrated in Figure 26 with detailed parameters that were set in Tool 1 (2012) in Table 7. For each subcase, CO_2 pressure is assumed to be brought up to 80 bara downstream the onshore storage before the pipeline transport. This pressure is taken as the system boundary for all the subcases.

For subcase 1, 2 and 4, the outlet pressure is the wellhead pressure that was calculated based on the storage reservoir. For these subcases additional pumping was required. For case 3, the outlet pressure was selected based on the boundary pressure of 80 bar and the pressure drop, therefor for this subcase no additional pumping was required.

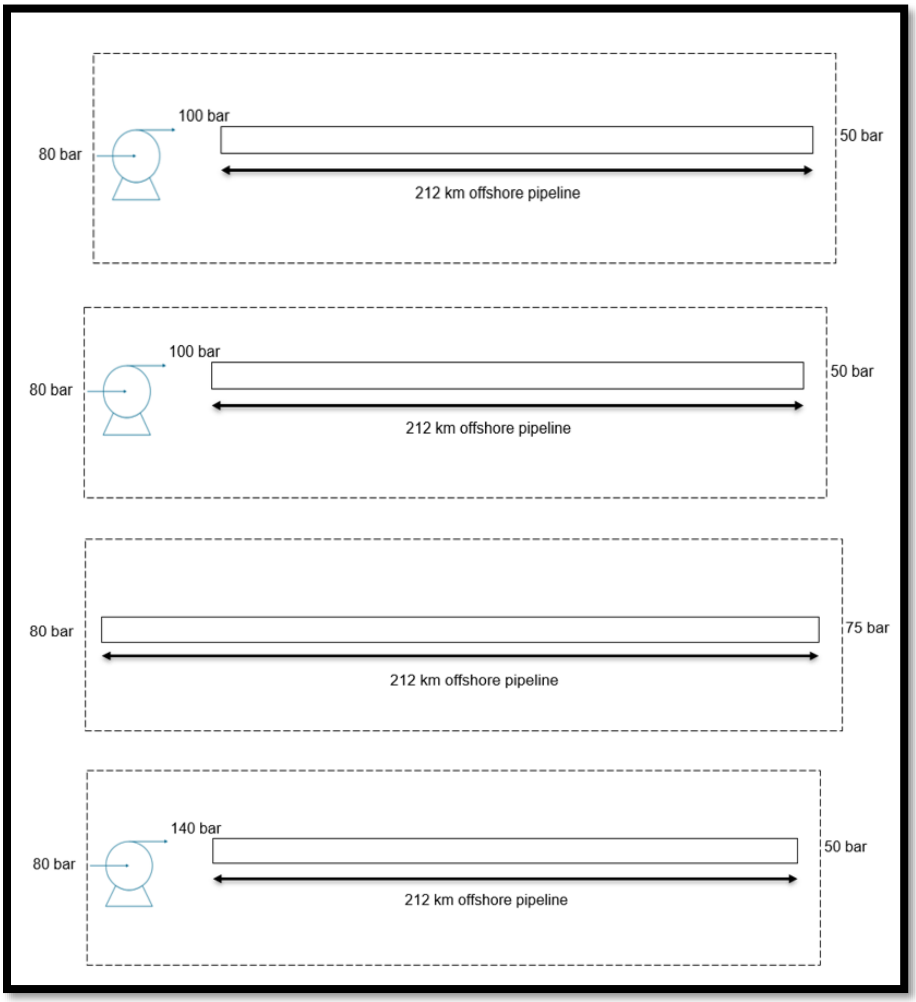


Figure 26: Overall design of transport system of Pipe A subcases (a) subcase 1 (b) subcase 2 (c) subcase 3 (d) subcase 4 (top to bottom)

Table 7: Detailed design parameters of Pipe A subcases

Pipe A	1	2	3	4
Characteristics	Re-use pipeline full capacity – 20 MTPA	New built- Fitted pipeline- 20 MTPA	Re-use pipeline Limited flow rate – 5 MTPA	New built- Fitted pipeline- 5 MTPA
Source	Onshore storage with undefined CO_2 source			
Length of pipeline (km)	212			
Outer diameter (inch)	30	30	30	16
Internal diameter (inch)	28.74	28.74	29.02	15.08
Pipeline thickness (mm)	15.9	15.9	12.7	11.9
Flowrate (MTPA)	20	20	5	5
Lifetime (years)	7	7	25	25
System boundary pressure (bar)	80			
Pipeline Pressure drop (bar)	50	50	5	90
Inlet pressure of transport system (bar)	100	100	80	140
Outlet pressure (bar)	50	50	75	50

5.3.3 Pipe A Case Results & Discussion

Table 8: Pipe A case cost results from Tool 1 (2012)

	Case 1	Case 2	Case 3	Case 4
Description	Re-use pipeline full capacity – 20 MTPA, 7 years	New built- Fitted pipeline- 20 MTPA, 7 years	Re-use pipeline Limited flow rate, 5 MTPA, 25 years	New built- Fitted pipeline- 5 MTPA, 25 years
Total cost (M€)	31	515	22	297
Total CAPEX (M€)	8	491	5	262
Total OPEX (M€)	24	24	17	35
Cost/unit (€/t)	0.3	5.0	0.4	5.6
Cost/Unit/length (€/t/km)	0.01	0.12	0.02	0.28

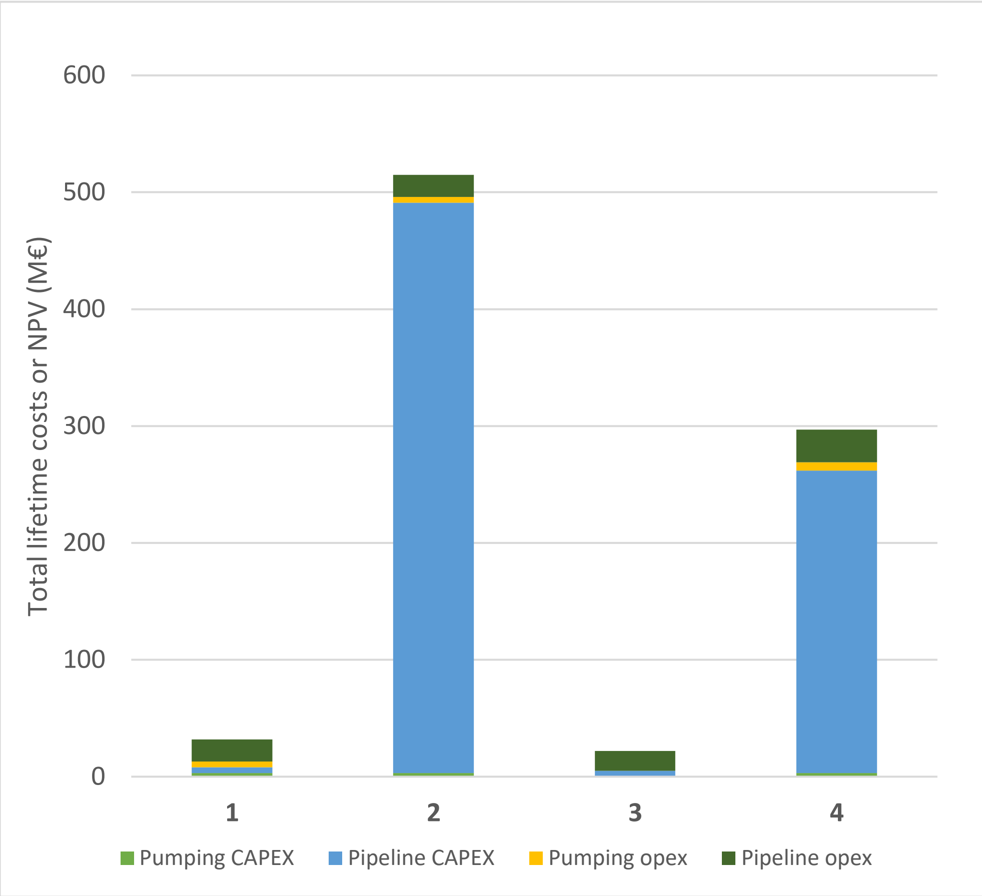


Figure 27: Split cost results for Pipe A case

Table 8 shows the results from Tool 1 (2012) obtained for each subcase of re-use of Pipe A. For the case of re-use pipeline against new built pipeline operating at full capacity of 20 MTPA, reusing Pipe A saves 484 M€ of lifetime costs which is around 94 % cost savings compared to new built case. For the case of re-using Pipe A against new built for a limited flow rate of 5 MTPA, re-use case saves 275 M€ of lifetime costs which is about 92 % of cost savings. Overall re-using Pipe A to transport CO_2 can potentially result in cost savings greater than 90 % compared to new built case and reduce transport cost per ton by 4.7 – 5.2 €. The main contributors to the lifetime costs of Pipe A cases from Figure 27 are pipeline CAPEX for case 2 and case 4 (new built cases) and pipeline OPEX for case 1 and case 3 (re-use cases).

Table 9 shows the lifetime emissions from the Pipe A transport system of GHG (converted to CO_2 equivalent) for each subcase. New built options have higher lifetime emissions. The emissions are dominated by GHG emissions from pipeline material construction (refer to Figure 28). Re-use pipeline subcases have lower GHG emissions that are mainly generated during operation of pipeline. Re-use of pipeline with full capacity compared to new built allows avoidance of over 500 kt_{CO2e} of CO_2 equivalent over the lifetime (reduction of emissions by 96 %). Re-use pipeline for limited flow rate compared to new built reduces emissions by 89 % (avoidance of 250 kt_{CO2e}). Overall, the new built case for full capacity (subcase 2 from Table 9) emits 0.43 % of the total transported volume of CO_2 over the lifetime and emissions from re-use cases are almost negligible.

Table 9: Pipe A case emissions from Tool 1 (2012)

	Case 1	Case 2	Case 3	Case 4
Description	Re-use pipeline full capacity – 20 MTPA, 7 years	New built- Fitted pipeline- 20 MTPA, 7 years	Re-use pipeline Limited flow rate, 5 MTPA, 25 years	New built- Fitted pipeline- 5 MTPA, 25 years
Total emissions (kt_{co2})	22	595	29	275
Efficiency (t_{CO2e}/t_{CO2})	0.02 %	0.43 %	0.02 %	0.22 %

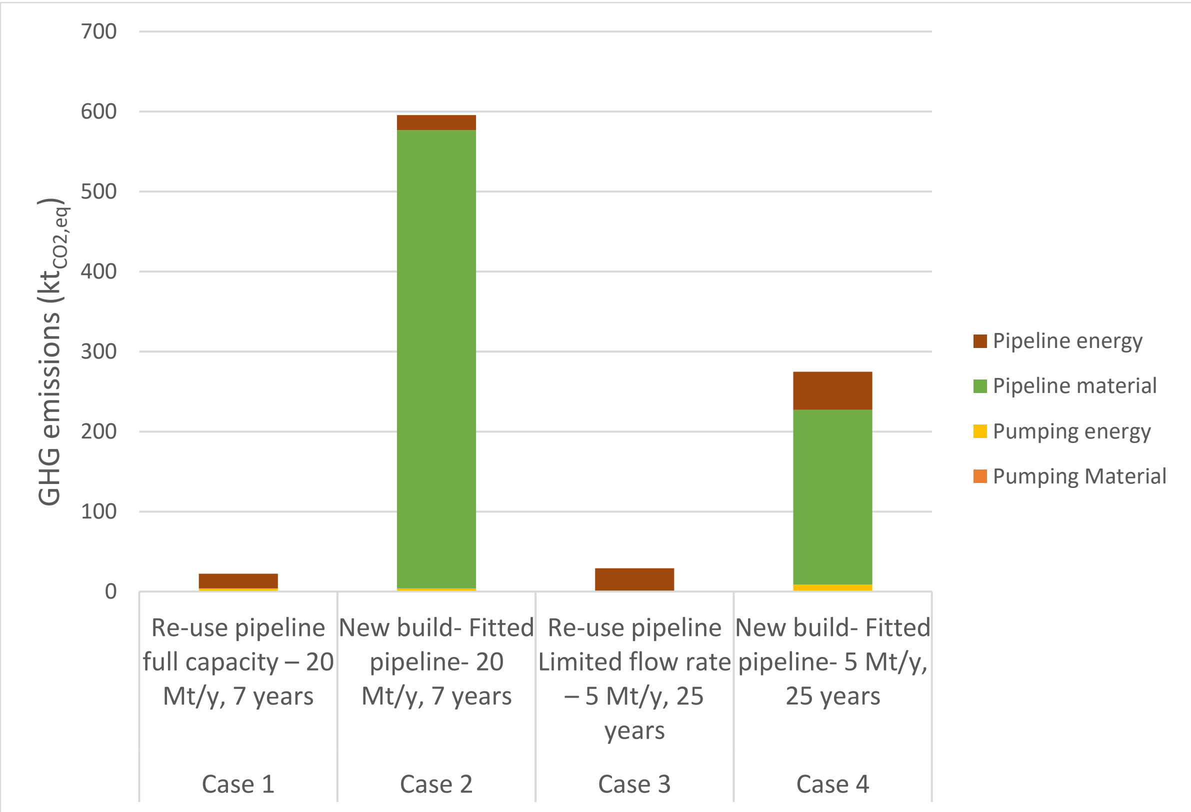


Figure 28: GHG emissions from Pipe A case

5.4 Pipe B Case

5.4.1 Case description

Pipe B is an existing offshore pipeline starting from Germany and ending in a storage area in the NCS. The pipeline is 600 km long and with an outer diameter of 40-inch. This pipeline has a capacity to transport more than 20 MTPA of CO_2. In this case around 16 MTPA of CO_2 is assumed to be captured from an industrial plant in Germany and stored in NCS storage area. Three subcases for Pipe B shown in Figure 29, were evaluated using Tool 1 (2012).

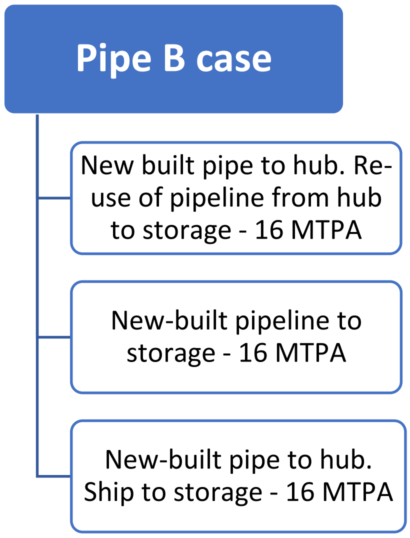


Figure 29: Pipe B subcases

5.4.2 Methods

For each subcase evaluated under Pipe B case, the transport system was simulated , and the input parameters were defined in Tool 1 (2012). The design of the transport system of the subcases of Pipe B are illustrated in Figure 30. The detailed parameters that were set in Tool 1 (2012) are shown in Table 10. The Pipe B subcases were analyzed for 25 years project lifetime and 16 MTPA flow rate of CO_2. A sensitivity analysis was performed for Pipe B subcases using Tool 1 (2012), where the flow rate was reduced from 16 MTPA to 1 MTPA. Overall design of transport for 1 MTPA Pipe B case, and the table of design parameters can be found in the Appendix on page 101 and page 102 of this report.

More sensitivity analyses were performed where parameters shown in Figure 31 were varied by some amount. The percentage change in lifetime costs and unit costs of Pipe B subcases compared to base case due to change in parameter values were recorded. The base case/central case results for each subcase under Pipe B are presented in Table 23 (page 102).

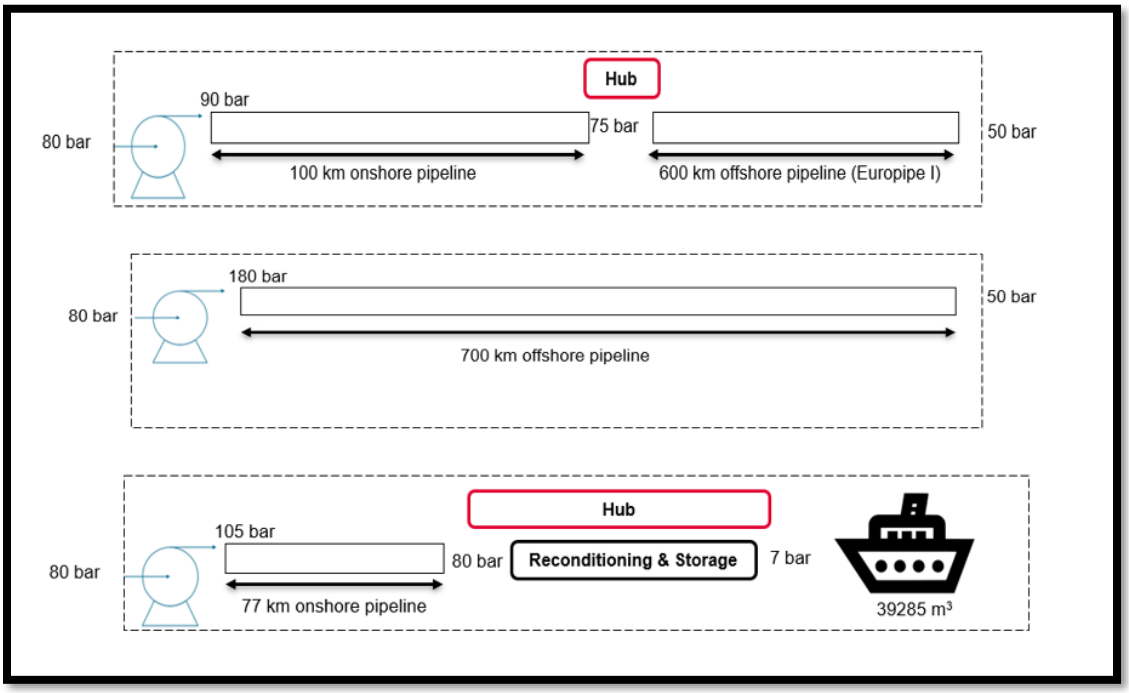


Figure 30: Overall design of transport system of Pipe B subcases (a) subcase 1 (b) subcase 2 (c) subcase 3 (top to bottom)

Table 10: Detailed design parameters of Pipe B subcases

Pipe B	1	2	3
Characteristics	New built- pipeline to hub. Re-use hub to storage	New built- pipeline to storage	Pipeline to hub (onshore). Ship to storage
Source	Germany		
Distance by ship (km)			630
Ship size (t)			45 374
Length of pipeline (km)	100, 600	700	70
Outer diameter (inch)	30 40	30	26
Internal diameter (inch)	28.74 38.74	27.87	24.76
Pipeline thickness (mm)	15.9 15.9	27	15.9
Pressure drop (bar)	40	130	25
System boundary pressure (bar)	80		
Inlet pressure of transport system (bar)	90	180	105
Outlet pressure (bar)	50	50	80

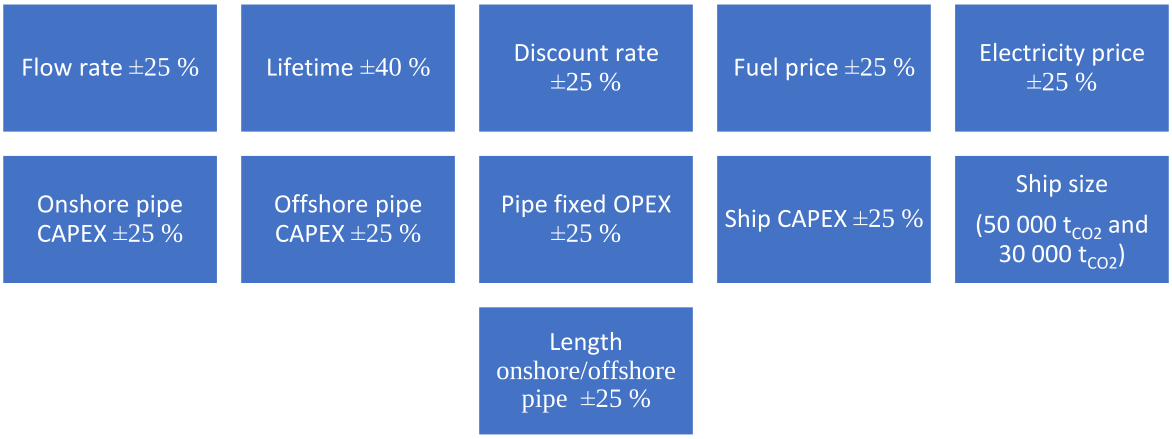


Figure 31: Changes in parameters from the central case for sensitivity analysis of lifetime costs and unit cost of Pipe B subcases

5.4.3 Pipe B case Results & Discussion

Table 11: Pipe B subcase cost results from Tool 1 (2012)

	Case 1	Case 2	Case 3
Description	16 MTPA, new pipeline to hub, re-use of Pipe B to storage	16 MTPA, new pipeline to storage	16 MTPA, pipeline to hub, ship to storage
Total cost (M€)	211	1657	1503
Total CAPEX (M€)	150	1545	567
Total OPEX (M€)	61	112	936
Cost/unit (€/t)	1.2	9.7	8.8
Cost/Unit/length (€/t/km)	0.02	0.15	0.13

Table 11 shows the results from Tool 1 (2012) obtained for each subcase of Pipe B. For the case of re-use pipeline (case 1) against new built pipeline to storage (case 2) transporting 16 MTPA, reusing Pipe B saves 1.4 B€ of lifetime costs which is around 87 % cost savings. For the case of re-using pipeline against shipping transport option (case 3), re-use case saves 1.3 B€ of lifetime costs which is about 86 % of cost savings. CO_2 transport by ship (case 3) saves 150 M€ of lifetime costs compared to new built offshore pipeline to storage (Case 2) (cost savings of 10 %). Overall re-using Pipe B to transport CO_2 can potentially result in cost savings between 85 and 90 % compared to new-built case and reduce transport cost per ton by 7.5 – 8.5 €. The main contributors to the lifetime costs of Pipe B subcases from Figure 32 are offshore pipeline CAPEX for case 2 and ship OPEX for case 3.

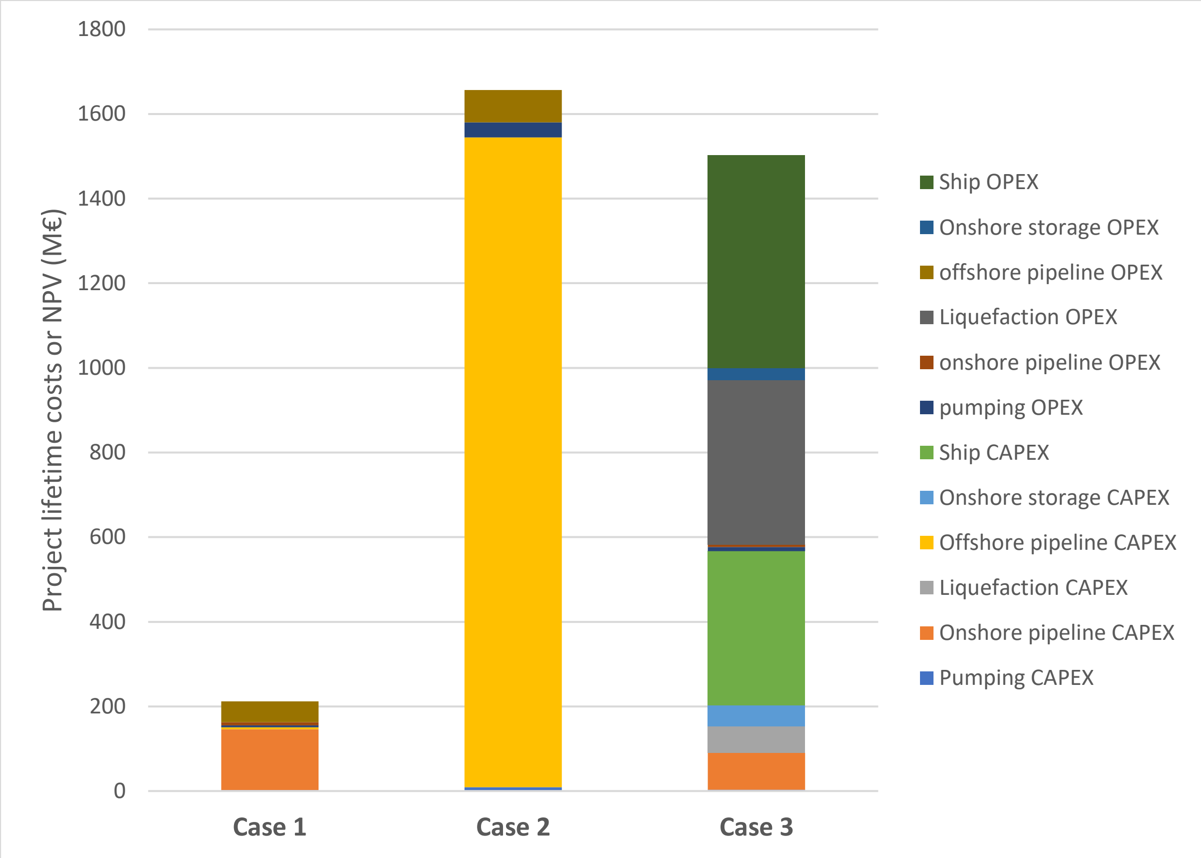


Figure 32: Total split cost results for Pipe B case

Table 12 shows the lifetime emissions from the Pipe B transport system of GHG (converted to CO_2 equivalent) for each subcase. New built pipeline (case 2) has higher lifetime emissions dominated by emissions from offshore pipeline material construction (refer to Figure 33). Re-use pipeline subcase have lower GHG emissions that are mainly coming from construction of onshore pipeline in case 1. Re-use of Pipe B compared to new built allows avoidance of over 2 Mt_{CO2e} over the lifetime (reduction of emissions by 87 %) and avoidance of 5.3 Mt_{CO2e} compared to shipping transport (reduction of emissions by 95 %). New built offshore pipeline to storage allows avoidance of 3.3 Mt_{CO2e} compared to ship transport. Overall reuse of Pipe B was able to reduce emissions of transport by 0.5-1.3 % per ton of CO_2 according to Tool 1 (2012) calculations and although shipping transport seems more economical than new built pipeline, it emits approximately two times more CO_2 than the pipeline.

Table 12: Pipe B case emissions

	Case 1	Case 2	Case 3
Description	16 MTPA, new pipeline to hub, re-use of Pipe B	16 MTPA, new pipeline to storage	16 MTPA, pipeline to hub, ship to storage
Total emissions (kt_{co2})	303	2268	5609
Efficiency (t_{CO2e}/t_{CO2})	0.08 %	0.57 %	1.40 %

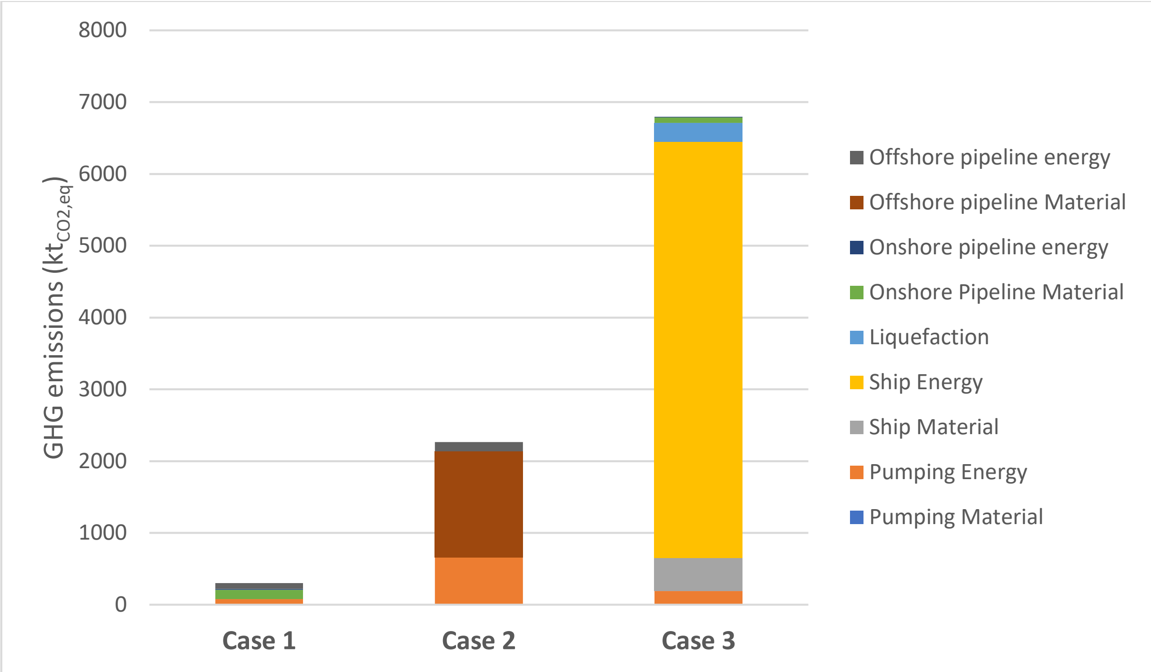


Figure 33: GHG emissions from Pipe B case from Tool 1 (2012)

When Pipe B subcases are simulated in Tool 1 (2012) at a lower flowrate of 1 MTPA, total costs for subcase 1, re-use of Pipe B, has 32 % lower costs than if the flow rate is 16 MTPA. This is due to smaller size of onshore pipe required to reach the hub from the capture site and no pumping requirements before pipe export. For the new built pipeline (case 2), 1 MTPA flow rate results in decrease of total costs by almost 50 % compared to 16 MTPA flow rate, due to smaller size of pipeline selected for the former. Shipping transport (case 3) shows a decrease by 73 % in total costs for 1 MTPA flow rate as a result of smaller size ship and smaller onshore pipeline required in such a case. The details are shown in Table 13. Overall, for low flow rates, re-use pipeline is still more economical than new built options and when new built pipeline is compared with the ship transport, ship transport is the preferred option from cost point of view.

Table 13: Pipe B case for 1 MTPA cost results from Tool 1 (2012)

	Case 1	Case 2	Case 3
Description	1 MTPA, new pipeline to hub, re-use of Pipe B to storage	1 MTPA, new pipeline to storage	1 MTPA, pipeline to hub, ship to storage
Total cost (M€)	144	873	412
Total CAPEX (M€)	82	811	262
Total OPEX (M€)	62	62	150
Cost/unit (€/t)	13.5	81.8	38.6
Cost/Unit/length (€/t/km)	0.21	1.25	0.59

The emission results for the lower flowrate of 1 MTPA are shown in Table 14. For case 1 (re-use), for 1 MTPA the emissions over lifetime of the transport system is half of what is estimated for 16 MTPA (Table 12). For case 2 the lifetime emissions have reduced by 70 % and for case 3 there are reductions of 78 % when the flowrate is decreased from 16 MTPA to 1 MTPA. For 1 MTPA flowrate, ship transport is almost 95 % efficient (emits 5 % of CO_2 that is being transported over the lifetime of the project) while for 16 MTPA flowrate, ship transport is almost 99% efficient.

Table 14: Pipe B case got 1 MTPA emissions from Tool 1 (2012)

	Case 1	Case 2	Case 3
Description	1 MTPA, new pipeline to hub, re-use of Pipe B to storage	1 MTPA, new pipeline to storage	1 MTPA, pipeline to hub, ship to storage
Total emissions (kt_{co2})	154	680	1255
Efficiency (t_{CO2e}/t_{CO2})	0.62 %	2.72 %	5.02 %

Figure 34 and Figure 35 show the sensitivity analysis results of unit transport and lifetime costs for re-use of Pipe B case (subcase 1). The total lifetime costs show the highest sensitivity for this case to onshore pipeline length, onshore pipeline unitary CAPEX and the flowrate. For unit transport cost the highest sensitivity (Figure 35) is to flow rate, onshore pipeline length, lifetime and onshore pipe CAPEX.

Increasing the length of onshore pipeline from 100 km to 125 km (+25 %) led to an increase in lifetime costs of 24 % according to Figure 34 and decreasing the length from 100 km to 75 km reduced the lifetime costs by 11 %. The reason for such change is that at longer distances, a larger diameter pipeline is suitable while for shorter distance smaller pipelines can be used. These would have an impact on the lifetime costs. Increase in onshore pipeline CAPEX by 25 % resulting in increase in lifetime costs by 17 % and vice versa is also an obvious result. When the flow rate is increased from 16 MTPA to 20 MTPA (+25 % change) the lifetime costs increase by 14 % due to larger flow rates requiring larger diameter of pipeline which increases the lifetime costs. However, when the flow rate is reduced to 12 MTPA, the reduction of lifetime costs is only 5 %.

As flow rate decreases by 25 %, the unit transport cost increases by 27 % as economics of scale are reduced. A smaller sized pipe will be used for lower flow rates that would reduce the total lifetime costs that is now spread over a lower amount of CO_2. Increasing the onshore pipe length or increasing onshore pipe unitary CAPEX both result in increase in unit transport cost by 23 % and 17 % respectively due to the increase in total lifetime costs for the same amount of CO_2.

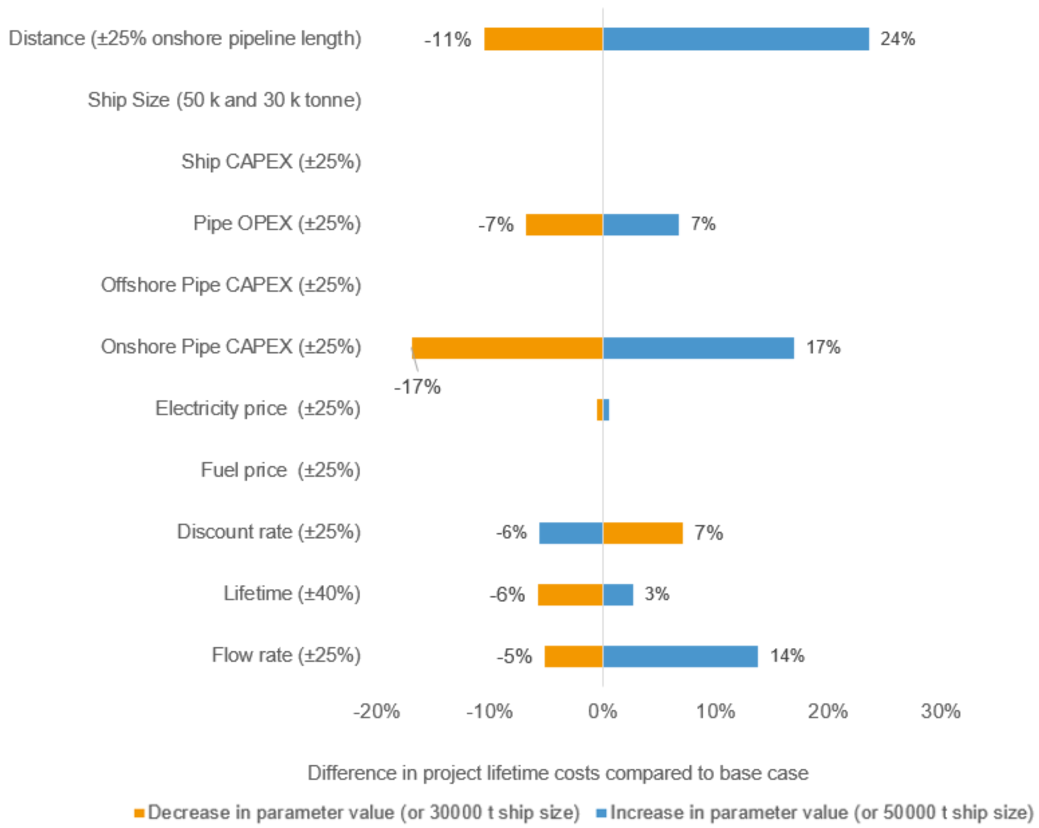


Figure 34: Sensitivities of lifetime costs of re-use Pipe B subcase 1 using Tool 1 (2012)

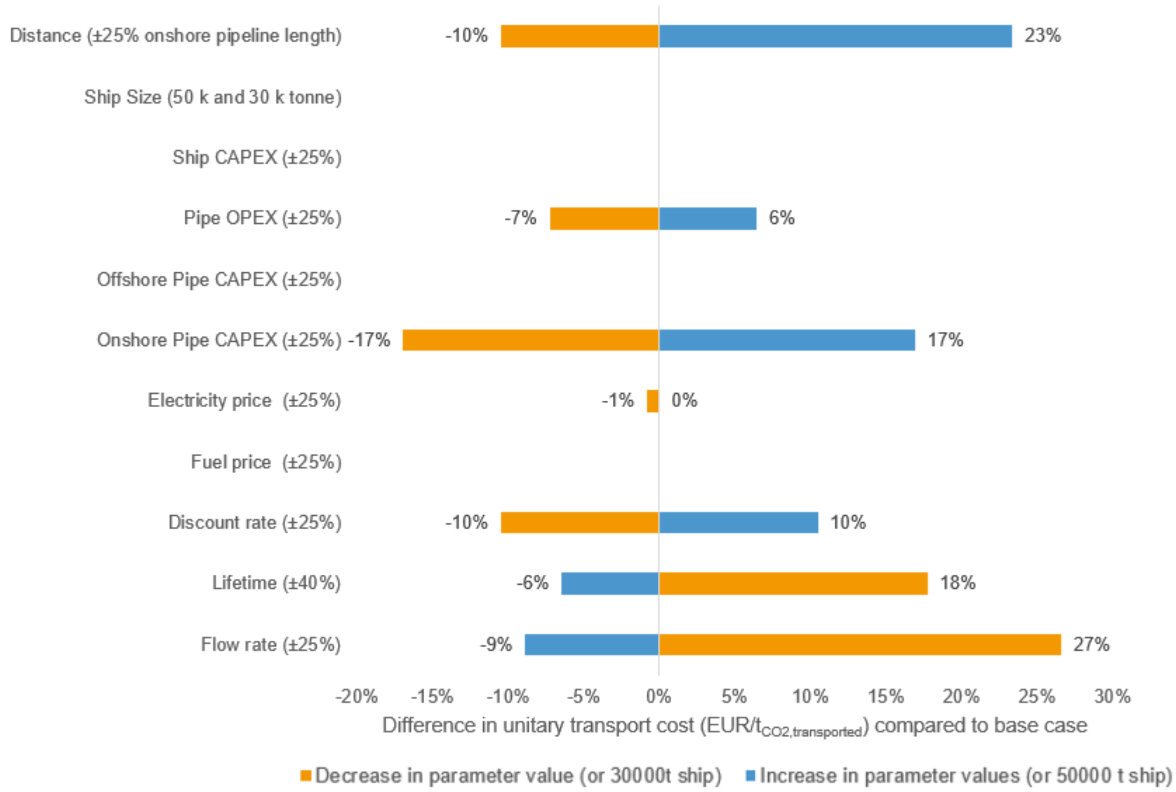


Figure 35: Sensitivities of unit transport costs of re-use Pipe B subcase 1 using Tool 1 (2012)

Figure 36 and Figure 37 show the sensitivity analysis results of unit transport and lifetime costs for new built offshore pipeline in Pipe B case (subcase 2). The total lifetime costs show the highest sensitivity for this case to offshore pipeline length (distance), offshore pipeline unitary CAPEX and the flowrate. For unit transport cost the highest sensitivity (Figure 37) is to offshore pipeline length (distance), offshore pipe CAPEX, lifetime and flow rate.

Increasing the length of offshore pipeline from 700 km to 875 km (+25 %) led to an increase in lifetime costs of 31 % according to Figure 36 and decreasing the length from 700 km to 525 km reduced the lifetime costs by 24 %. The reason for such change is that at longer distances, a larger diameter pipeline is suitable while for shorter distances smaller pipelines can be used. Increase in offshore pipeline CAPEX by 25 % results in increase in lifetime costs by 23 % and vice versa is also an obvious result. When the flow rate is increased from 16 MTPA to 20 MTPA (+25 % change) the lifetime costs increase by 13 % due to larger flow rates requiring larger diameter of pipeline which increases the lifetime costs. However, when the flow rate was reduced to 12 MTPA, the reduction of lifetime costs is only 7 %.

As flow rate decreases by 25 %, the unit transport cost increases by 23 % as economics of scale are reduced. A smaller sized pipe will be used for lower flow rates that would reduce the total lifetime costs which is now spread over a lower amount of CO_2. Increasing the offshore pipe length or increasing offshore pipe unitary CAPEX both result in an increase in unit transport cost by 31 % and 23 % respectively due to the increase in lifetime costs for the same amount of CO_2.

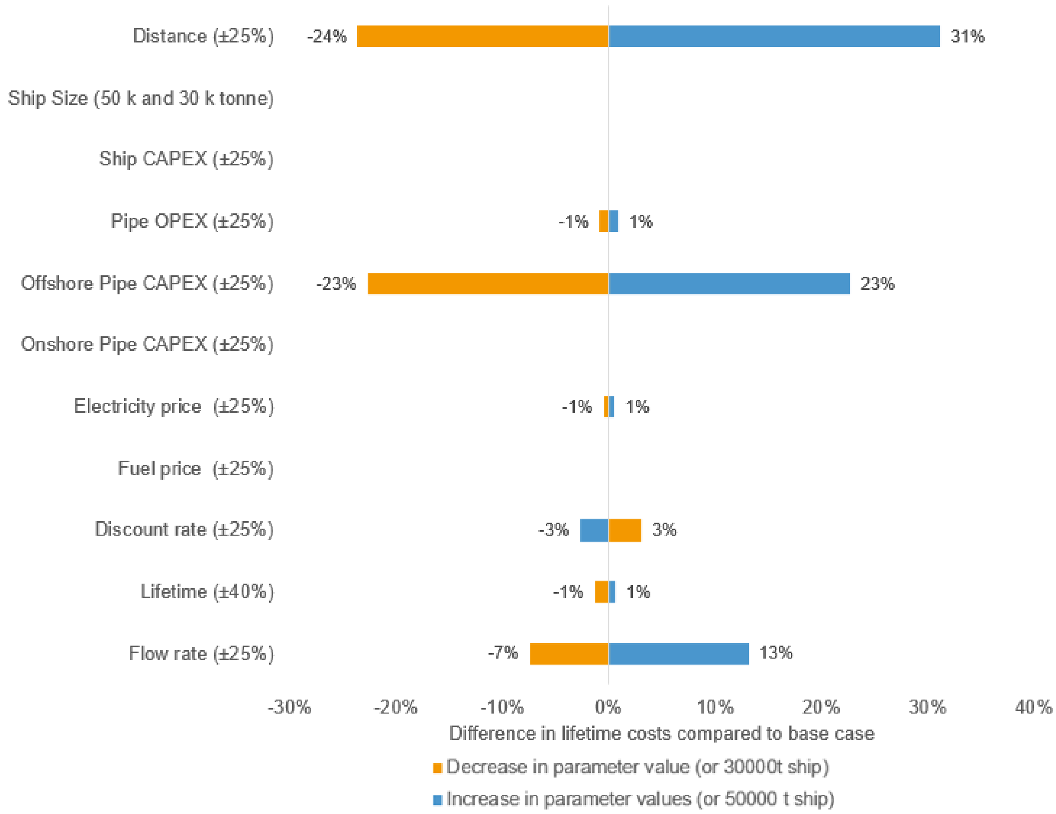


Figure 36: Sensitivities of lifetime costs of newbuilt pipeline option Pipe B subcase 2 using Tool 1 (2012)

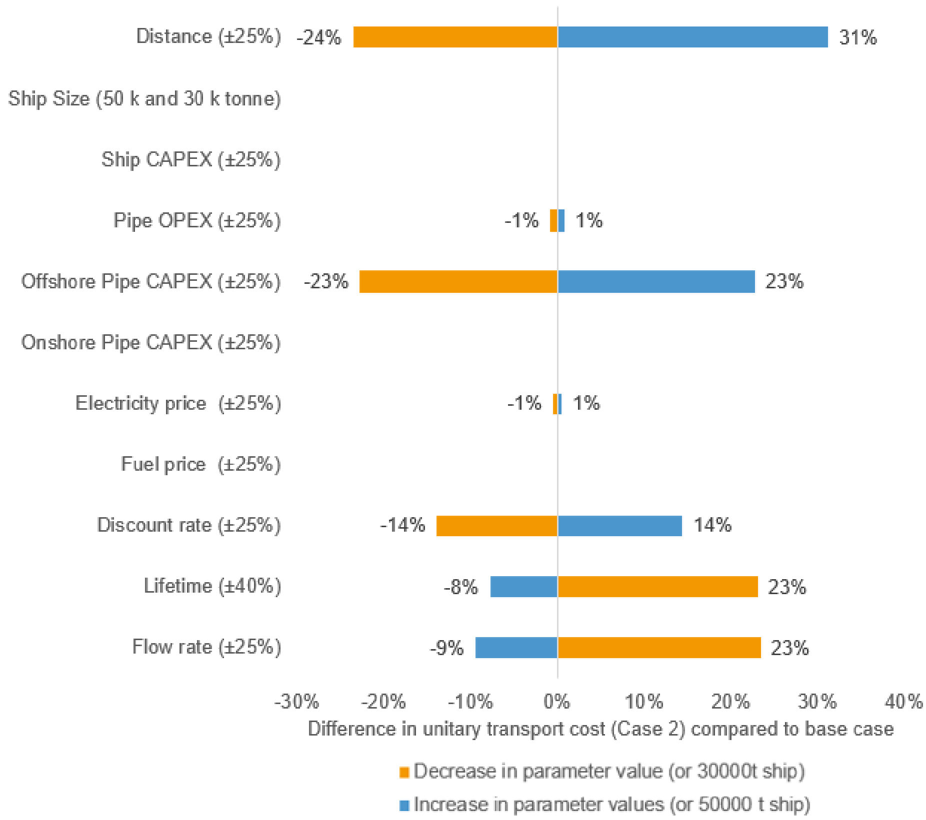


Figure 37: Sensitivities of unit transport costs of newbuilt pipeline option Pipe B subcase 2 using Tool 1 (2012)

Figure 38 and Figure 39 show the sensitivity analysis results of unit transport and lifetime costs for ship transport option in Pipe B case (subcase 3). The lifetime costs show the highest sensitivity for this case to flow rate and discount rate. For unit transport cost the highest sensitivity (Figure 39) is to lifetime and shipping distance.

When the flow rate is increased from 16 MTPA to 20 MTPA (+25 % change) the lifetime costs increase by 27 % due to larger flow rates requiring larger size of ship to transport CO_2 consequentially increasing the lifetime costs. When the flow rate is reduced to 12 MTPA, the reduction of lifetime costs is 24 %. Increasing the discount rate from 8 % to 10 % (+25 %) can lead to a reduction in lifetime costs by 10 % according to Figure 38 and decreasing the discount rate from 8 to 6 % can lead to an increase in the lifetime costs by 13 %. The reason for such change is that at higher discount rates, the value of money decreases more than it would decrease for a central case discount rate. This results in decrease in lifetime costs. A lower discount rate than base case would result in higher NPV.

A shorter lifetime (reducing the lifetime from 25 years to 15 years) led to a 9 % increase in unit cost due to CAPEX being spread over less amount of CO_2. A longer lifetime (increase in lifetime from 25 years to 25 years) led to a reduction in unit transport cost by 3 %. Using a 30000 t_{CO2} ship size (compared to 45374 t_{CO2} ship size) increases unit transport cost by 8 % due to a greater number of ships required to transport 16 MTPA of CO_2. Increase in shipping distance by 25 % leads to higher unit transport cost due to higher lifetime costs spread over the same amount of CO_2.

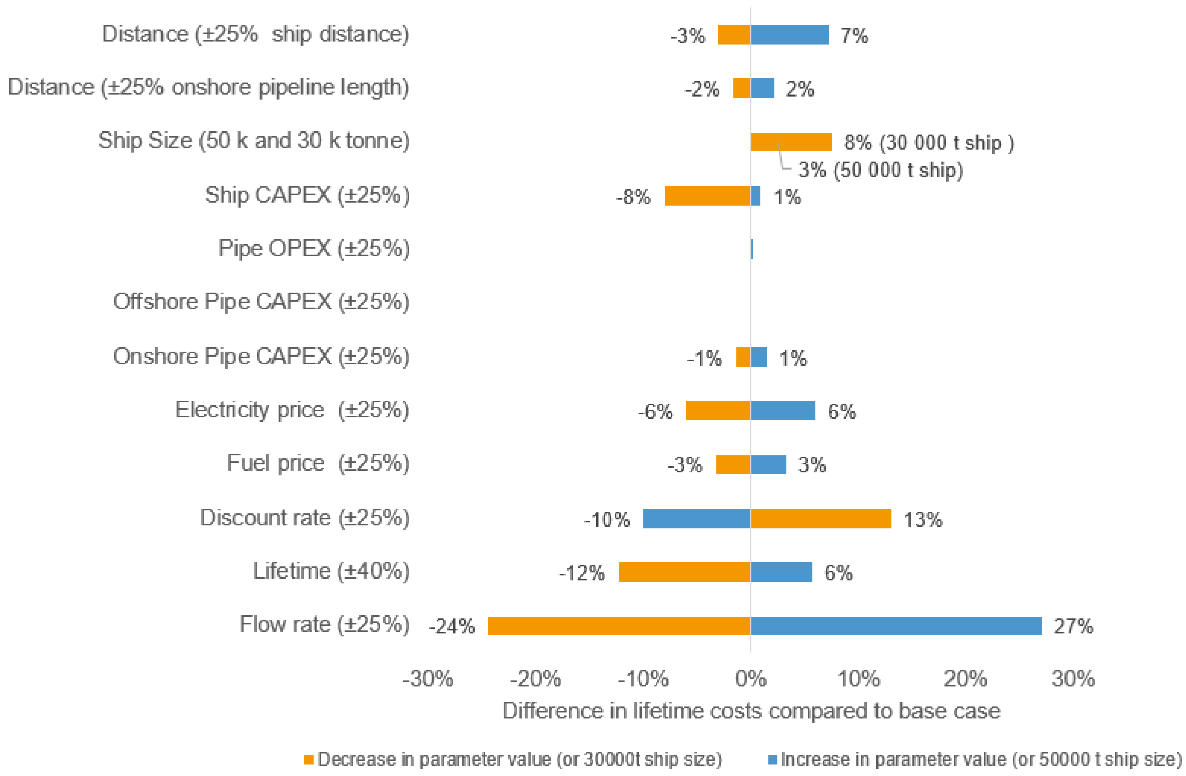


Figure 38: Sensitivities of lifetime costs of shipping transport option Pipe B subcase 3 using Tool 1 (2012)

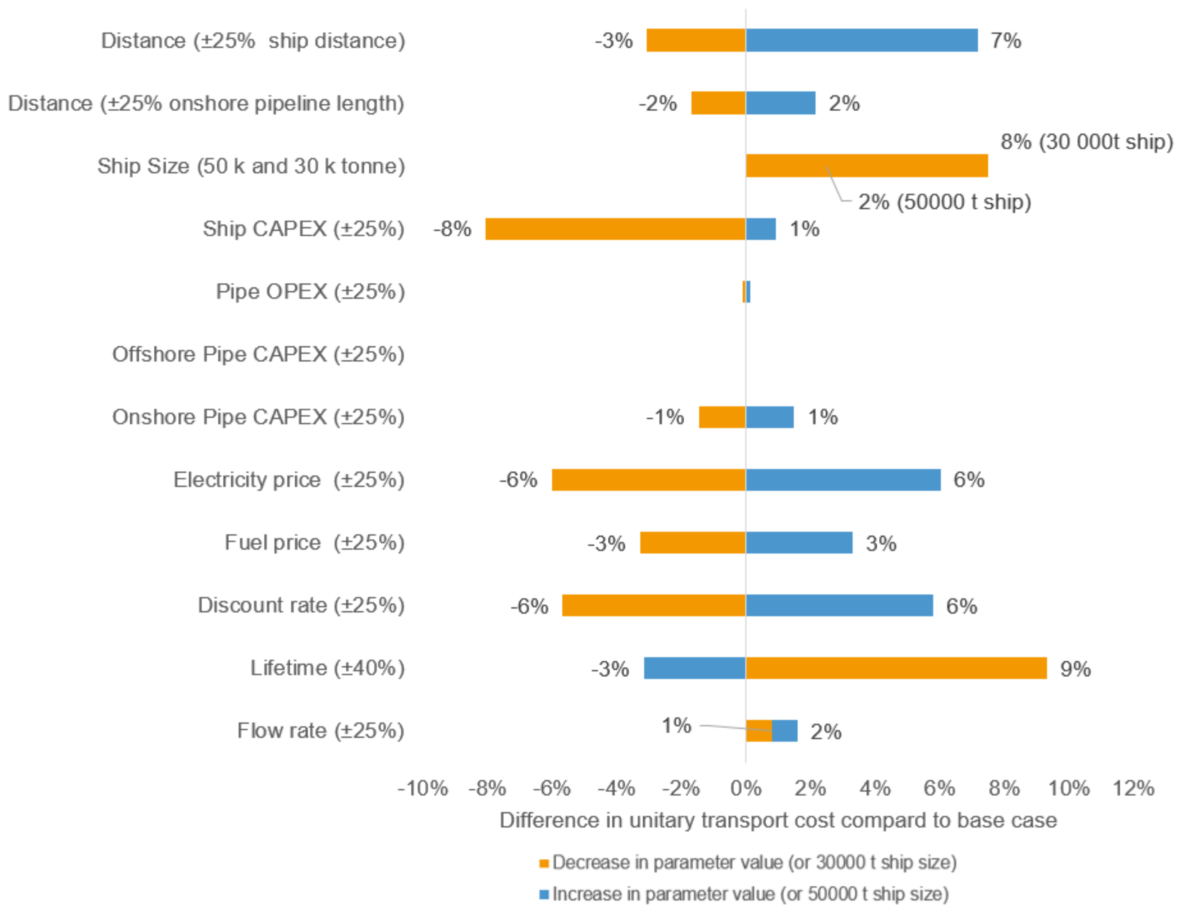


Figure 39: Sensitivities of unit transport costs of shipping option Pipe B subcase 3 using Tool 1 (2012)

5.5 Tool 1 (2012) version vs Tool 1 (2017) version

In this section a quick comparison was made between results obtained from the older version of Tool 1, referred to as Tool 1 (2012), and the new version of Tool 1, referred to as Tool 1 (2017), for CO_2 transport chains that were a part of 'Re-use of existing pipeline' project at Total E&P Norge. 'Pipe B' operated by a Company in Norway is a natural gas pipeline that is around 670 km long and it transports gas from North Sea to the Continental Europe. In 'Re-use of existing pipeline' project, re-use of Pipe B was assessed to transport CO_2 and compared against new-built offshore pipeline and shipping transport. Both versions of Tool 1 had the same parameters defined in the input sheet and the results were compared.

Figure 40 shows the lifetime costs obtained from the two tools. For case 1 (re-use of Pipe B), Tool 1 (2012) gave 211 M€ as lifetime costs whilst Tool 1 (2017) showed 14 % higher lifetime costs resulting at 241 M€. The difference comes from fixed annual OPEX between the versions. OPEX in Tool 1 (2017) was taken as 1.5 % of CAPEX per year while in Tool 1 (2012) it was taken as 6 % CAPEX per year. In this case there was no CAPEX since the pipeline infrastructure already existed, user factor section of parameters sheet in pipeline module was then used where resulting CAPEX of pipeline was set as zero, therefore Tool 1 (2012) and Tool 1 (2017) calculated annual OPEX as a percentage of estimated CAPEX. Pigging costs for existing pipeline of 5 M€ was added as CAPEX for case 1. It should be noted here that fixed OPEX in Tool 1 (2012) is independent of the pipe diameter and remains the same for pipes of different sizes. However, in Tool 1 (2017), fixed OPEX of pipe changed with changing pipeline diameter.

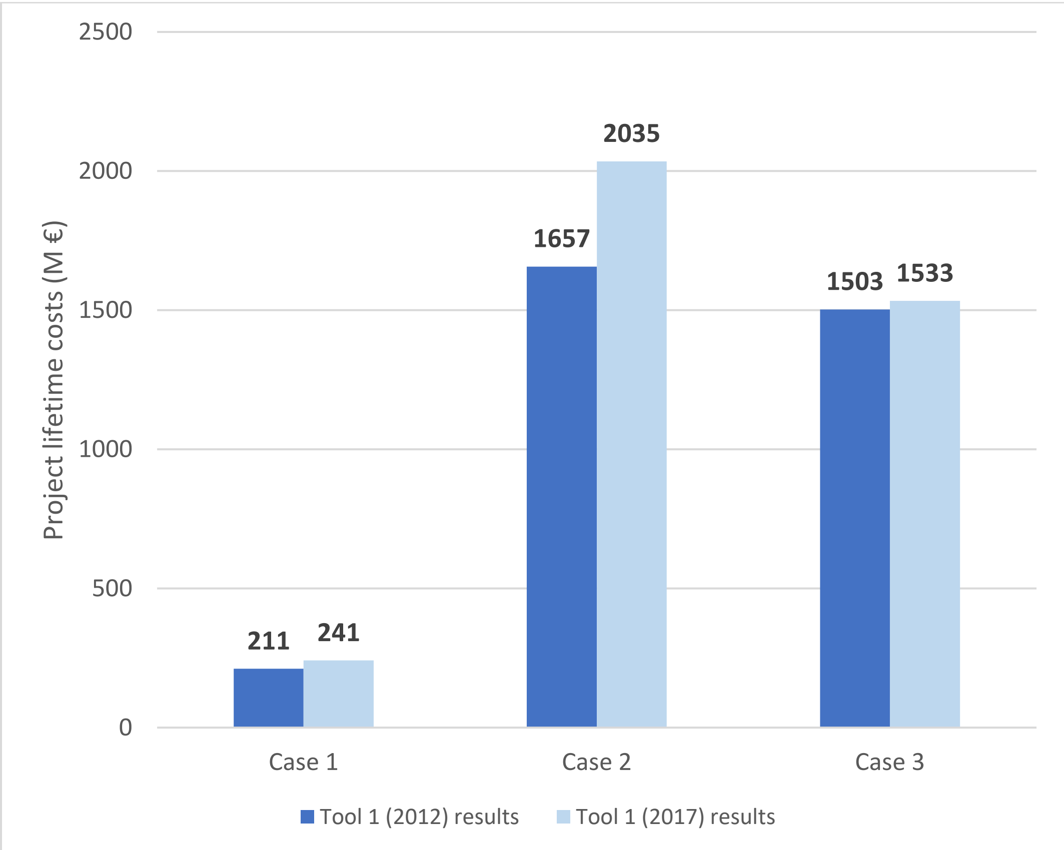


Figure 40: Pipe B case comparison between Tool 1 (2012) and Tool 1 (2017)

For case 2 (new built offshore pipeline), Tool 1 (2017) showed 23 % higher lifetime costs than Tool 1 (2012) due to differences in unitary CAPEX and fixed OPEX of pipeline. The change in CAPEX between the tools was due to Tool 1 (2017) using an improved cost model for its pipeline obtained from Knoope et al. (*Knoope, Guijt, Ramirez, & Faaij, 2014*), where Right-Of-Way, onshore-offshore landfall, labor cost, material cost and miscellaneous costs are taken into account for CAPEX. Offshore pipe CAPEX and fixed OPEX in Tool 1 (2017) are 81050 €/inch/km and 36472 €/km/year, while in Tool 1 (2012) it is 71065 €/inch/km and 7665 €/km/year.

Case 3 (shipping transport) showed that the difference in lifetimes costs between the two versions is less than 2 %. There have not been any updates in cost model for shipping transport in Tool 1 (2017).

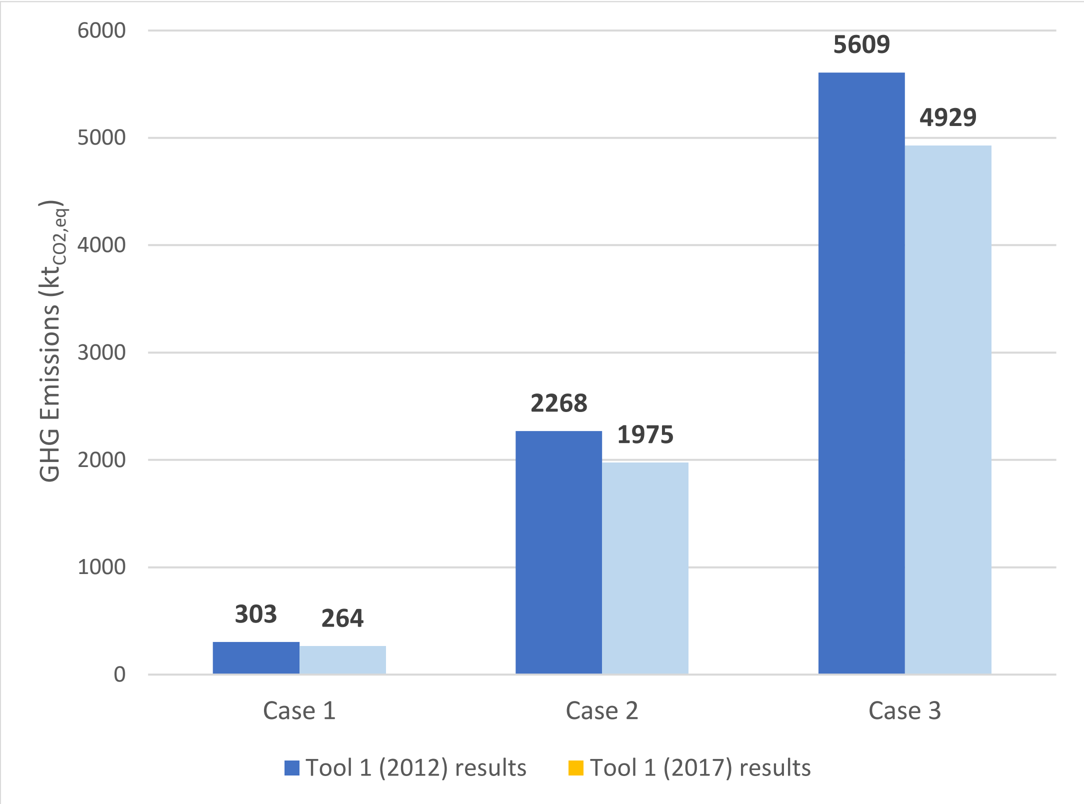


Figure 41: Pipe B case emissions comparison from Tool 1 (2012) and Tool 1 (2017)

Figure 41 shows the lifetime emissions from the transport system over the 25-year time duration that is presented in both tools. Case 1 (re-use of Pipe B) showed emissions from Tool 1 (2017) are 13 % lower than Tool 1 (2012) due to the difference in climate impact factors used in the analysis between the two tools. Tool 1 (2012) used a higher fixed OPEX climate impact factor of 0.657 kg_{CO2e}/USD_{2002} and for a riser pipeline it was 1.157 kg_{CO2e}/USD_{2002} (data obtained from Economic Input-Output LCA Carnegie Mellon tool) . Tool 1 (2017) used updated climate impact factors (updated to 2016 levels) and fixed OPEX impact factor as 0.624 kg_{CO2e}/USD_{2002}. A similar result was noted for case 2 (newbuilt offshore pipeline).

For case 3 (shipping transport), Figure 41 shows 12 % lower emissions reported by Tool 1 (2017) compared to Tool 1 (2012).The reason for the difference was that Tool 1 (2012) used heavy fuel oil for reconditioning of CO_2 on-board and therefore used climate impact factor of 3.564 kg_{CO2e}/USD_{2002}, while Tool 1 (2017) used Liquefied Natural Gas (LNG) as fuel for reconditioning which has a lower climate impact factor of 2.75 kg_{CO2e}/USD_{2002}.

5.6 Key findings from Chapter 5

- Re-use of existing pipelines can result in significant cost savings compared to new built. Within this study it has been shown that a cost saving of 90-95 % for a relatively short distances (approximately 200 km) and a cost saving of around 85-90 % for a longer distance (600 km) can be achieved when a re-use is compared to a new-built case.
- It has been shown once more that for long distance transport, ship transport is more economical than a pipeline transport if the pipeline is to be newly built. However, re-use of an existing pipeline is still the most economic option.
- Both Tool 1 (2012) and Tool 1 (2017) were able to simulate the transport systems studied within this chapter, however Tool 1 (2017) gave a more reliable estimate due to updated cost levels, updated pipeline cost models and updated climate impact factors using in the tool.
- The tools gave a good indication and decent estimation of economic and environmental benefits of re-use of existing pipelines compared to new-built options.
- Re-use of infrastructure can prove to be beneficial economically and environmentally, if challenges and technical hurdles are overcome such as availability of structure, location of CO_2 sources nearby and state of the infrastructure to support CO_2 transport.

6 Effects of pipeline dimensions on costs of CO_2 transport

6.1 Business case objective

The objective here was to study the effect of varying pipeline dimensions on the transport cost and lifetime emissions in an offshore CO_2 transport scenario.

6.2 Materials & Methods

For the techno-economic and environmental assessment of this business case, Tool 1 (2017) version of the simulation tool was used. The dimensions of the offshore pipeline to be investigated were defined by CO_2 transport sub-project lead, at Total E&P Norge as follows:

Transport type:	Offshore pipeline
Length of pipeline:	125 km
Operational Lifetime:	25 years
CO_2 Flow rate:	1.5 MTPA
Well-head pressure:	80 bar
Real discount rate:	8 %
Pump inlet pressure:	15 bar
Pump efficiency:	75 %
Electricity cost:	55.5 €/MWh

Two subcases were investigated as part of the business case.

6.2.1 Sub-case 1: Pipeline diameter

The pipeline diameters investigated were 10.75-inch and 12.75-inch OD. Schematic diagram of the transport system for both pipelines can be seen in Figure 42. Results from Tool 1 (2017) transport simulation module were recorded and compared. A centrifugal pump is placed before the pipeline to increase the pressure of incoming CO_2 from 15 bar to a desired pipeline pressure. A quick estimation of pump costs was conducted where the pump requirements and costs were calculated based on a formula obtained from *McCollum and Ogden (2006)*[23]. Energy required by pump is a function of maximum flowrate through the pump, pressure drop across pump, pump efficiency and density of CO_2.

[23] *(McCollum & Ogden, 2006)*

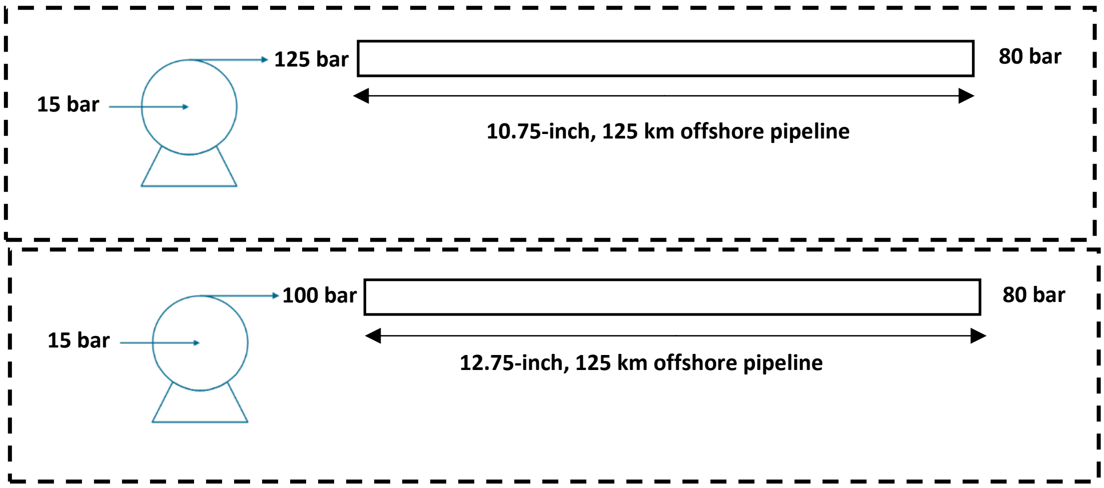


Figure 42: Schematic diagram for 10.75 and 12.75-inch pipeline case

6.2.2 Sub-case 2: Wall thickness

For this case, two pipeline diameters of 10.75-inch or 12.75-inch OD were selected. The wall thickness was varied by ±50 % for each case. The simulations were run in Tool 1 (2017) in which the pressure drops were calculated according to the pipeline dimensions ensuring that the outlet pressure matches the wellhead pressure of 80 bar. 80 bar outlet pressure was chosen to ensure dense phase in the pipeline. The effect of wall thickness on CO_2 transport cost and emissions was calculated.

6.3 Results & Discussion

6.3.1 Sub-case 1: Pipeline diameter

The cost and emission results for the two pipe sizes are shown in Table 15. The efficiency in Table 15, is the total emissions of CO_2 equivalent over the lifetime of transport project over the total amount of CO_2 transported in that time period.

Table 15: Summary of techno-economic and environmental assessment results for comparison between two different pipeline diameters[24],[25]

Pipeline OD (“)	Total CAPEX (M€)	Total Fixed OPEX (M€)	Total variable OPEX (M€)	TOTAL Discounted lifetime cost (M€)	CO_2 transport cost (€/$t_{CO2,transported}$)	Total Emissions ($kt_{CO2,eq}$)	Efficiency (%)
10.75	116	40	9	128	8.0	64	0.17
12.75	131	45	7	143	9.0	72	0.19

[24] All costs are given in $€_{2016}$
[25] Detailed breakdown of costs is attached in the **APPENDIX**

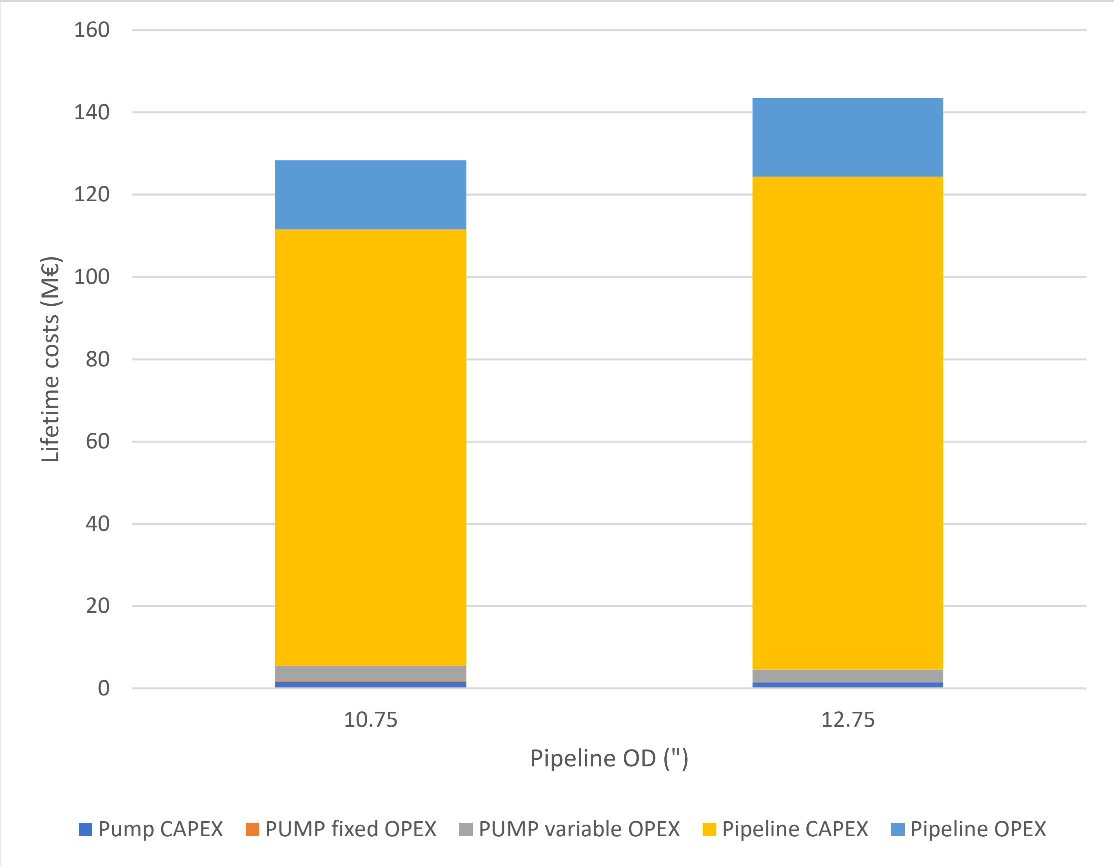


Figure 43: Visual representation of cost comparison between two pipelines of different diameters

If the 10.75-inch pipeline is taken as a baseline scenario, when the pipeline diameter is increased by one size up the total lifetime costs increases by 12 % (~ 15 M€). Figure 43 illustrates the cost components that make up the total lifetime costs of each case. The larger pipeline has 12 % higher lifetime costs compared to the smaller pipeline. This is due to larger pipeline requiring more material for construction (21 % higher material cost) and thus higher labor cost for construction (19 % higher). According to Figure 43, the lifetime costs are dominated by pipeline CAPEX and OPEX, where pipeline CAPEX is a function of material, labor, onshore-offshore landfall and miscellaneous costs. A 12.75-inch pipeline compared to a 10.75-inch pipeline would require more material and hence cost more in terms of labor. Emissions for construction and operation of a large pipeline is around 15 % higher than the smaller pipeline.

In both pipeline case, the pump size and CAPEX were estimated to be slightly different from each other due to the change in pressure drop across the pump. Pressure drop across the pump is directly proportional to the energy required by the pump. The smaller pipeline needed higher energy to pump CO_2 from 15 bar to 125 bars compared to the larger pipeline, therefore the pumping costs were high. Since the flowrate studied in this section is very low, pump costs are quite small compared to overall transport cost.

Larger pipelines have higher pipeline CAPEX and therefore higher OPEX (which is a set 1.5 % of CAPEX per year) which is why overall 12.75-inch pipeline has higher total discounted lifetime costs as seen in Figure 43.

6.3.2 Sub-case 2: Wall thickness

The impact of wall thickness on total cost and GHG emissions have been investigated for two pipeline sizes using Tool 1 (2017) and summarized in Table 16 below.

For the smaller pipeline (10.75-inch OD), as shown in Table 16, when the wall thickness is increased by 50 % compared to the base case, the total lifetime cost increases by almost 9 % (11 M €) (refer to Figure 44). On the other hand, when the wall thickness is halved compared to the base case, lifetime cost reduces by 6 % (8 M€ lower than the base case). For the 12.75-inch pipeline, when the wall thickness is increased by 50 % the lifetime cost only increases by 5 %. When the wall thickness is decreased by 50 % compared to the base case, costs decrease by 6 %.

Table 16: Summary of techno-economic and environmental assessment results for varying wall thickness of pipelines[26]

Pipeline OD (")	Wall thickness	Total CAPEX (M€)	Total Fixed OPEX (M€)	Total variable OPEX (M€)	TOTAL Discounted lifetime cost (M€)	CO_2 transport cost (€/$t_{CO2,transported}$)	Total Emissions ($kt_{CO2,eq}$)	Efficiency (%)
10.75	Base case	116	40	9	128	8.0	64	0.17
10.75	+50%	126	43	9	139	8.7	74	0.20
10.75	-50%	109	37	8	120	7.5	57	0.15
12.75	Base case	131	45	7	143	9.0	72	0.19
12.75	+50%	138	47	7	151	9.5	80	0.21
12.75	-50%	123	42	7	134	8.4	64	0.17

The lifetime emissions for the pipelines (10.75-inch and 12.75-inch) when the wall thickness is increased by 50 % is 16 % and 11 % higher than the base case respectively. The emissions are 11% lower than the base case when the wall thickness is reduced by 50 % for both pipeline sizes.

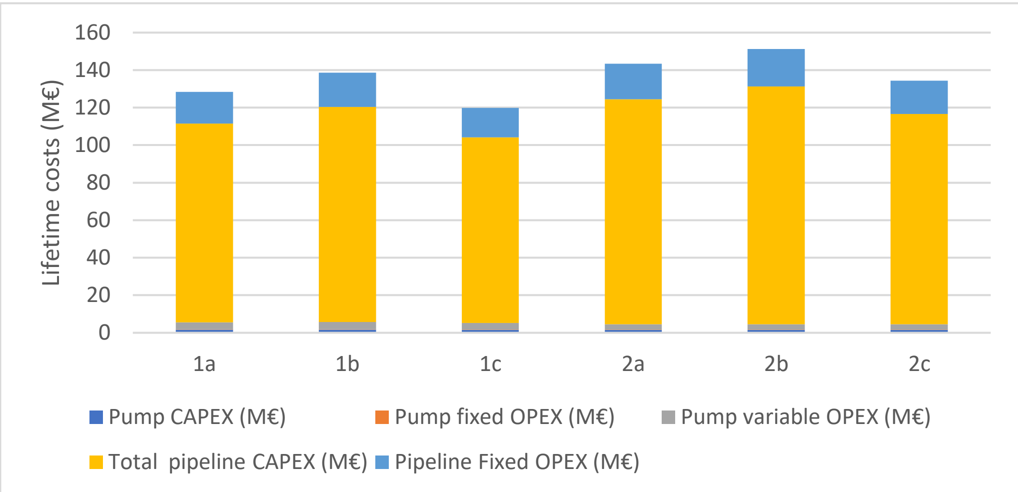


Figure 44: Visual representation of cost comparison between pipeline with ±50 % thickness

[26] Further details of each of the cases are shown in **APPENDIX**.

6.4 Key findings from Chapter 6

- For the case of increasing pipeline diameter from 10.75 inch to 12.75 inch (125 km pipeline) can increase the lifetime costs by 12 % (15 M€) , unit transport cost by 1 €/$t_{CO2,transported}$ and life-cycle emissions by 13 % (~8 kt_{CO2e}).
- For 10.75 and 12.75-inch pipeline, varying wall thickness by ±50 % has very limited benefit on costs of pipeline.

7 Summary & Identification of gaps in Tool 1 for techno-economic and environmental assessment of CO_2 transport chain

In order to qualify current available tools on techno-economic and environmental assessment of CCS related projects, and to quantify the potential benefits of those activities, several cases were simulated in the tools and the costs and carbon footprint results were compared. Three main themes of the report represented the three main tasks of the thesis: Assessment of MP versus LP ship transport, reuse of infrastructure for CO_2 transport and effects of pipeline dimensions on costs of CO_2 transport.

The fourth chapter covered techno-economic and environmental assessment of a business case from North of France which highlighted assessment of shipping option at different transport pressures (LP and MP). The purpose of this chapter was to determine a cost-optimal transport option for the concepts studied as a business case. One of the key findings is that at longer distances, shipping transport is a more economical option, however it emits more GHG than pipeline transport, therefore a solution is required to reduce the emissions from ships. Overall, the most important message from this chapter is that LP ship option is more cost-effective compared to MP ship based on calculations from techno-economic and environmental assessment tools.

The fifth chapter covered the topic of re-using infrastructure for CO_2 transport, where Tool 1 was used to assess different cases which included re-use and newbuilt options. The costs and carbon footprint of all the cases were compared with each other to conclude that re-using infrastructure can lead to over 80 % cost savings (for specific cases) and significant emission reductions compared to new built cases. Parameter sensitivity analysis was performed to identify the key parameters that lifetime and unit transport costs are most sensitive to. These parameters were identified to be flowrate, pipeline length or shipping distance and project duration.

The sixth chapter covered a brief assessment of CO_2 transport by pipeline by varying the pipeline diameter and the pipe wall thickness, in order to understand by how much pipeline dimensions, affect the lifetime costs and emissions.

After a detailed analysis of both versions of Tool 1, for the purpose of techno-economic and environmental assessment of CCS related projects and possible business cases some gaps in the Tool 1 (2012) were identified. Tool 1 (2012) had several issues that were addressed and improved in Tool 1 (2017) such as:

- Flexibility in choosing ship sizes and user specific ship characteristics.
- Flexibility in choosing buffer storage tank size and number of buffer storages tanks.
- Visibility of cost split of pipe CAPEX and improved cost model for pipelines.
- Updates in cost levels.

The gaps in Tool 1 (2017) that have not been addressed are the following:

- The tool is not able to assess costs for multiple ships of different sizes.
- The tool does not have the option of estimating costs for conditioning of pre-pressurized CO_2 (i.e. the tool does not allow user to change inlet conditioning parameters).

- The number of compressions stages for conditioning before export are fixed and cannot be changed.
- The tool cannot be used to estimate costs for CO_2 streams containing impurities.
- Different transport pressures (7 bara and 15 bara) for shipping are not available in the ship transport module.
- The tool uses Nth-of-a-kind cost methodology and not First-of-a-kind (investment costs are lower than what they actually are currently).

8 Suggested way forward

1. More techno-economic and environmental assessments should be carried out of pipeline dimensions and its effects on total lifetime costs. (i.e. consider evaluating larger sized pipeline of different lengths and thickness)
2. The new version of Tool 1 (2017) should be assessed like the Tool 1 (2012), to analyze the effect of improvements that were made by the research organization based in Norway and to further identify more gaps in the new version of the tool.
3. Techno-economic and environmental assessment should be performed over the whole CCS chain to understand the importance of CO_2 transport costs in the overall chain costs.
4. Suggest the possibility and urgency of integrating transport module for CO_2 with impurities and module for ship transport at different pressure into Tool 1 (2017).
5. Address the gaps in Tool 1 (2017) mentioned in the previous section to the research organization that developed it, to see the possibility of improvements.
6. Assess the environmental impact assessment module of Tool 1 by simulating several cases with already known results for comparison. This should be done to identify the strengths and weaknesses of GHG assessment module of Tool 1 (2017).
7. Evaluate if improvements in the Tool 1 (2017) would be more beneficial compared to developing an internal tool, that can be developed based on what the company would like to see.
8. Investigate and assess the benefits of on-board CO_2 capture in reducing emissions from shipping transport for long distances. In addition, evaluate the possibility of integrating on-board capture technology into Tool 1 (2017).

9 Conclusions

Three techno-economic and environmental assessment tools were evaluated by comparing the results of case simulations, which represented ongoing R&D activities and potential business cases. The tools were Tool 1 (2012), Tool 1 (2017) and Tool 2.

Overall Tool 1 is a comprehensive techno-economic and environmental assessment tool, which allows user to simulate components of CCS chain based on their specific characteristics. It provides technical results such as utilities consumption and breakdown of costs into CAPEX and OPEX, as well as breakdown of emissions related to construction and operation of transport systems. The tool is adequate to be used on its own and it has a user-friendly interface. In terms of results obtained from Tool 1, when comparing it with Tool 2, the difference in costs were within acceptable range (±15 %). Currently there are several gaps identified in the tool, such as the tool is not able to assess ship transport at different pressures and it cannot be used to assess CO_2 streams containing impurities. In summary, if these gaps are addressed then Tool 1 (2017) would be sufficient for assessing CO_2 transport systems from R&D perspective. This tool would be competitive to other available tools.

Tool 2 mainly focuses on shipping transport costs and does not include environmental impact assessment. The tool gives the user less flexibility in selecting different parameters and placing user specific characteristics for ships. Although all the data that the tool uses to develop techno-economic models are visible to the user, the tool always displays results or options that are cost-optimal. In summary, Tool 2 is a less developed and more rigid version of Tool 1.

Through the assessments that were performed by Tool 1 (2012), Tool 1 (2017) and Tool 2, the following key findings can be concluded:

- Tool 1 (2017) has had improvements been made compared to Tool 1 (2012) version of the tool and it clearly gives better estimates of cost assessment results.
- Tool 1 (2017) is a sufficient tool for economic and environmental assessment of R&D projects covering all types of pipeline and ship transport even though it can be further improved.
- Tool 2 has limited sizes of ships, limited flow rates and limited transport options that the user can select, compared to Tool 1 (2017). The tool can be used to assess flow rates between 0.5 and 10 MTPA and only looks at ship transport with very brief calculation of booster pump with offshore pipeline compared to Tool 1 (2017) that covers shipping between harbors, direct shipping, offshore and onshore pipe.
- These tools only provide a cost estimate as an indicator of areas for potential cost optimization and cannot be used to determine exact costs of CCS developments.

- At shorter distances, pipeline is more economical compared to ship, however at large distances despite being a cost-effective option, shipping emits large amount CO_2 over the lifetime of the project which needs to be addressed.
- When comparing MP and LP ship transport, LP liquefaction costs are greater due to higher energy requirement by refrigeration unit, however overall MP shipping infrastructure such as storages and ships are expensive. This results in LP shipping being slightly more economical than MP shipping option.

- Re-use of infrastructure for CO_2 transport can result in potential cost savings by 80% or higher and over 85 % emissions reduction compared to new built options for the specific business cases studied in the report.
- Re-use of infrastructure can be beneficial if challenges such as its availability and location of it from CO_2 capture and CO_2 storage location are overcome.
- Pipe length, pipe unitary CAPEX, flow rate and lifetime have significant impact on lifetime costs for re-use infrastructure and new built pipeline cases.
- For ship transport, flowrate, discount rate and distance have a significant impact on the lifetime costs.
- For a specific pipeline transport case, it is shown that changing the pipeline diameter might have a significant impact on total lifetime cost, while varying the wall thickness by ±50 % has very limited benefit.

10 References

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Appendices

The enclosed appendices are split into four sections (A to D)

APPENDIX A: Chapter 3 material

Table 17: Tool 2 storage assumptions

Transport pressure	CAPEX per t_{CO2} of storage capacity (£/t_{CO2})	OPEX (%CAPEX/year)
Low P	516	5
Medium P	795	5
High P	3 073	5

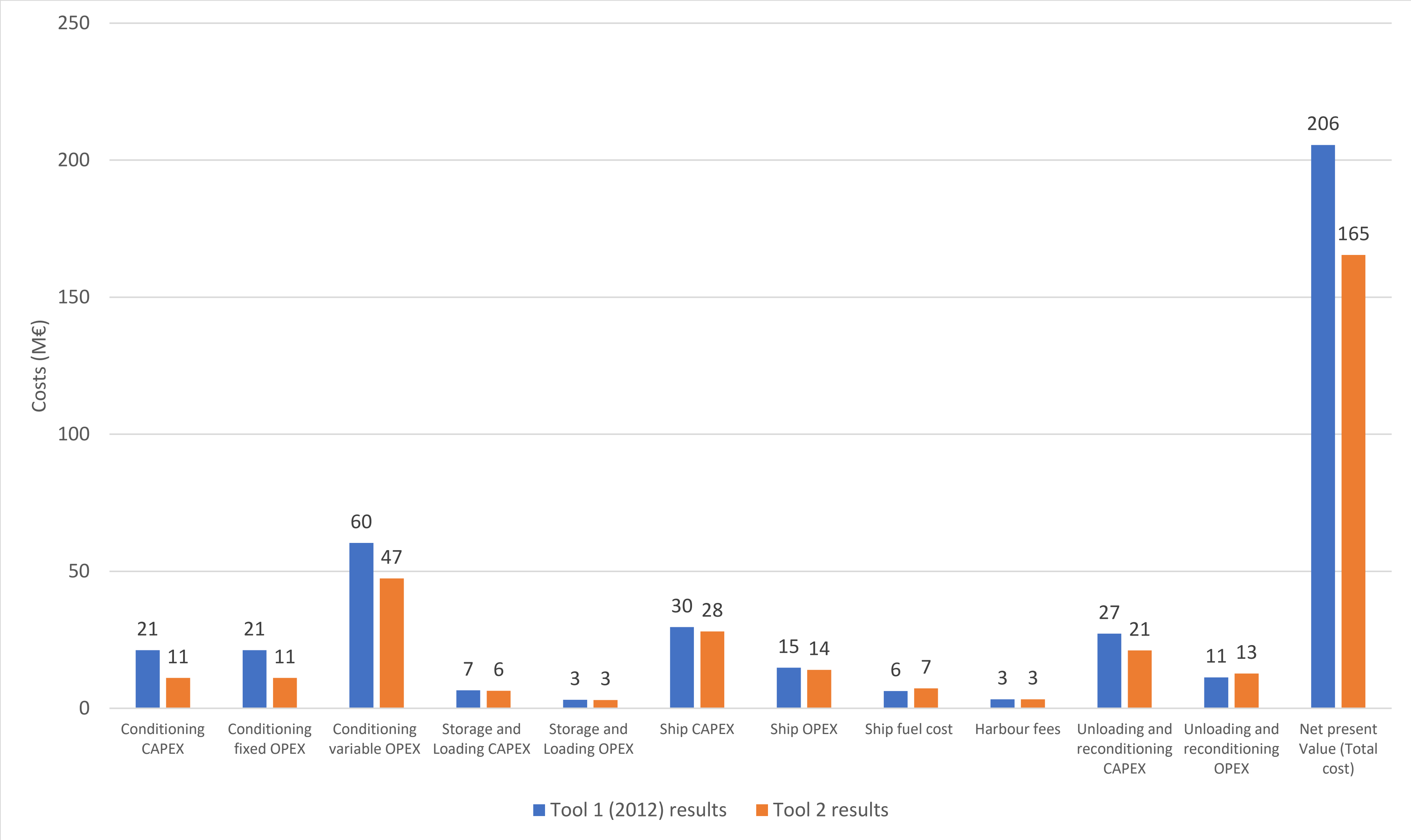

Figure 45: Conditioning and shipping to an offshore site from Tool 1 (2012) and Tool 2 for 0.5 MTPA, 600 km and 10 years

APPENDIX B: Chapter 4 Material

Table 18: Detailed cost results of Alternative #2A analysis using Tool 2 for shipping between harbors MP vs LP

Transport pressure & type	ship between harbors LP	ship between harbors MP
Distance (km)	1100	1100
Flow rate (MTPA)	1	1
Lifetime (years)	15	15
Suggested SHIP size (t_{CO2})	20000	20000
Number of ships	1	1
Liquefaction CAPEX (M€)	22.11	17.19
Liquefaction OPEX (M€)	33.16	25.79
Liquefaction fuel cost (M€)	142.15	113.29
Temporary CO_2 storage CAPEX (loading) (M€)	14.07	21.68
Temporary CO_2 storage OPEX (loading)(M€)	10.55	16.26
Loading CAPEX (M€)	1.56	1.56
Loading OPEX (M€)	0.70	0.70
Ship CAPEX(M€)	45.88	92.57
Ship OPEX (M€)	34.41	69.43
Ship fuel cost (M€)	16.34	16.34
Harbor fee (M€)	12.64	12.64
Unloading CAPEX (M€)	1.56	1.56
Unloading OPEX (M€)	0.70	0.70
Temporary CO_2 storage CAPEX (unloading) (M€)	14.07	21.68
Temporary CO_2 storage OPEX (unloading) (M€)	10.55	16.26
Gasification CAPEX (M€)	0.95	0.88
Gasification OPEX (M€)	5.63	5.35
Total Cost (M€)	367.05	433.91
CO_2 Transport cost (€/$t_{co2, transported}$)	24.47	28.93
CO_2 emissions from liquefaction (t_{CO2})	23976	19107
CO_2 emissions from ship (t_{CO2})	8886	8886
CO_2 emissions TOTAL (t_{CO2})	32862	27993

Table 19: Detailed cost results of Alternative #2A analysis using Tool 2 for shipping to an offshore site MP vs LP

Transport pressure	ship to an offshore site LP	ship to an offshore site MP
Distance (km)	1100	1100
Flow rate (MTPA)	1	1
Lifetime (years)	15	15
Suggested SHIP size (t_{CO2})	20000	20000
Number of ships	1	1
Liquefaction CAPEX (M€)	22.11	17.19
Liquefaction OPEX (M€)	33.16	25.79
Liquefaction fuel cost (M€)	142.15	113.29
Temporary CO_2 storage CAPEX (loading) (M€)	14.07	21.68
Temporary CO_2 storage OPEX (loading)(M€)	10.55	16.26
Loading CAPEX (M€)	1.56	1.56
Loading OPEX (M€)	0.70	0.70
Ship CAPEX (M€)	45.88	92.57
Ship OPEX (M€)	34.41	69.43
Ship fuel cost (M€)	17.18	17.18
Harbor fee (M€)	6.32	6.32
Unloading CAPEX (M€)	18.62	18.62
Unloading OPEX (M€)	13.97	13.97
Temporary CO_2 storage CAPEX (unloading) (M€)	0.00	0.00
Temporary CO_2 storage OPEX (unloading) (M€)	0.00	0.00
Gasification CAPEX (M€)	4.92	4.92
Gasification OPEX (M€)	10.11	9.85
Total Cost (M€)	375.72	429.34
CO_2 Transport cost (€/$t_{co2,transported}$)	25.05	28.62
CO_2 emissions from liquefaction (t_{CO2})	23 976	19 107
CO_2 emissions from ship (t_{CO2})	9 340	9 340
CO_2 emissions TOTAL (t_{CO2})	33316	28447

Comparison of Alternative #2B cost assessment results from Tool 2 and Tool 1 (2017)

- **Technical/Economic details:**
  - Distance of 1000 km
  - 2 ships of size 7500 t_{CO2}
  - Transporting CO_2 from North of France to Western Coast of Norway
  - 1 MTPA, 8% discount rate and 25 years project lifetime

Low Pressure (LP) Ship transport cost comparison between Tool 1 (2017) and Tool 2

Table 20: LP ship transport comparison of Tool 1 (2017) & Tool 2 results

Cost component	Tool 2 result	Tool 1 (2017) result	Reason
Conditioning CAPEX for LP transport (*M€*)	23.08	41.32[27]	• **unitary CAPEX**: Tool 1 (2017)→ 31 €/($t_{CO2,conditioned}$/yr) Tool 2 →19.5 €/($t_{CO2,conditioned}$/yr) • The scale factors of equipment costs were higher in Tool 1 (2017) compared to Tool 2. • Tool 1 (2017) used 85 % capacity of conditioning unit (meaning 1.176 MTPA is the capacity of conditioning while the actual conditioned volume is 1 MTPA). Tool 2 used 100 % conditioning capacity (of 1 MTPA) • Tool 2 uses liquefaction CAPEX that has been summarized from list of liquefaction CAPEX values from literature.

[27] The conditioning CAPEX is 39.71 $M€_{2016}$. It is converted to 2019 EURO using the inflation rate of 4.04% to give 41.32 $M€_{2019}$

Conditioning Fixed *OPEX* *(M€ /yr)*	2.31	2.27[28]	• Tool 2 gives fixed OPEX as 10 % CAPEX/year • Tool 1 (2017) gives fixed OPEX as 6 % CAPEX/year *(uses process overnight factor of 1.09)*
Conditioning Variable OPEX *(M€ /yr)*	9.89	8.44[29]	• Tool 2 uses LNG fuel to provide electrical energy to the liquefaction unit • Tool 1 (2017) tool used electricity to power the conditioning unit and cooling water for the heat exchangers.

[28] Conditioning CAPEX from Tool 1 (2017) tool is 39.71 M€ and process overnight factor is 1.09. So Fixed OPEX = (39.71/1.09) * 0.06 = 2.18 M $€_{2016}$/yr. The cost is converted to 2019 EUR value by multiplying by 1.0404 (4.04% overall inflation) to get 2.27 $M€_{2019}$.

[29] The cooling water utility cost is 0.04 €/m^3 and electricity is 65.2 €/MWh. Based on that the Variable OPEX is 8.11 $M€_{2016}$ → 8.44 $M€_{2019}$

			• Electrical consumption is lower for Tool 1 (2017) than Tool 2. • **Tool 1 (2017)**: 112 KWh/t_{CO2} • **Tool 2**: 104.2 kWh/t_{CO2}
Storage & Loading CAPEX *(M€)*	7.51	13.08[30]	• **Tool 2** assumes that storage size is 20 % higher than the ship size. The ship size selected was 8000 t_{CO2} (around 6900 m^3) The unitary storage CAPEX for Tool 2: **455 EUR/m^3.** Loading CAPEX: 1.58 EUR/t_{CO2} • **Tool 1 (2017)** tool assumes storage size is 25 % greater than ship size of 6510 m^3 (7500 t). Unitary storage CAPEX is **1038 EUR$_{2016}$/m^3.** Loading CAPEX: 2.63 EUR$_{2016}$/t_{CO2}
Storage & Loading Fixed OPEX *(M€/yr)*	0.34	0.59[31]	• **Tool 1 (2017)** uses the same 6 % as OPEX. • **Tool 2** uses storage fixed OPEX as 5 % of storage CAPEX and loading fixed OPEX as 3 % of loading CAPEX.

[30] Actual Storage and loading CAPEX is 12.57 M€$_{2016}$ → 13.08 M€$_{2019}$
[31] Storage and loading OPEX is 0.57 M€$_{2016}$/yr → 0.59 M€$_{2019}$/yr

Ships CAPEX *(M€)* (2 ships)	56.82	40.66[32]	• **Tool 2** compiled ship CAPEX for various ship sizes from many sources and a regression analysis curve was made. Based on that each ship of 8000 t_{CO2} size is 28.4 $M€_{2019}$ (some literature considered First of a kind 'FOK' cost methodology while others considered Nth of a kind cost methodology) • **Tool 1 (2017)** ship CAPEX for 7500 t_{CO2} ship size is 18.6 M€/ship. Tool 1 (2017) uses Nth-of-a-Kind cost methodology which assumes that the technology used is matured. The CAPEX for small size ships are found by performing regression analysis.
Ship Fixed OPEX *(M€ /yr)*	2.84	2.78[33]	• **Tool 2** gives ship fixed OPEX as 5 % of Ship CAPEX. • Tool 1 (2017) gives fixed OPEX that is 5-7 % of the CAPEX. [34]

32 Original Ship CAPEX for two ships of 7500 t_{CO2} size in Tool 1 (2012) is 39.08 $M€_{2016}$ → 40.66 $M€_{2019}$

33 Ship fixed OPEX given by Tool 1 (2012) is 2.67 $M€_{2016}$/yr → 2.78 $M€_{2019}$/yr . Ship fixed OPEX will be the same for MP and LP case.

34 Formula used to calculate Ship annual fixed OPEX= $[0.0846*(\text{Ship size in } m^3)^{0.315959}]$ (0.98386)

Ship fuel cost *(M€/yr)*	3.98	2.32[35]	• **Tool 2:** since 8000 t_{CO2} ship size was used due to the limitation of the tool, the fuel consumption of a ship of this capacity is slightly higher than of a ship of 7500 t_{CO2} size. Fuel consumption (LNG) was found for different ship sizes by linear regression analysis of fuel consumptions values from literature. • **Tool 1 (2017)** uses the same unitary fuel consumption provided by a case study. [36]
Harbor fees *(M€/yr)*	2.75	2.86[37]	• **Tool 2:** Harbor fees per round trip was found for different ship sizes by linear regression analysis of harbor fees from literature. Tool 2 calculates that the total number of trips needed by 2 ships of 8000 t_{CO2} size is **125**. • **Tool 1 (2017)** calculates the total number of trips as **139**. Tool 2 report was used to obtain unitary harbor fees for 2 ships of size 7500 t_{CO2}.

[35] Ship fuel cost is 2.23 $M€_{2016}$/yr→2.32 $M€_{2019}$/yr

[36] Formula for calculation unitary fuel consumption (t_{fuel}/t_{CO2}/km) = (- 4.55421×10^{-11}) x (Ship size in m^3) + (7.16974×10^{-6})

[37] Harbor fees in the tool is given as 2.75 $M€_{2016}$/ yr → 2,86 $M€_{2019}$/yr

Storage and unloading CAPEX *(M€)*	7.51	13.08[38]	• **Tool 2** assumes that storage size is 20 % higher than the ship size. The ship size selected was 8000 t_{CO2} (around 6900 m^3) The unitary storage CAPEX for Tool 2: **455 €/m³**. Unloading CAPEX: 1.58 €/t_{CO2} • **Tool 1 (2017)** assumes storage size is 25 % greater than ship size of 6510 m^3 (7500 t). Unitary storage CAPEX is **1082 €/m³.** Unloading CAPEX: 2.63 €/t_{CO2}
Storage and unloading Fixed OPEX *(M€/yr)*	0.34	0.59[39]	• **Tool 1 (2017)** uses 6 % as storage fixed OPEX and unloading fixed OPEX as 2 %. • **Tool 2** uses storage fixed OPEX as 5 % of storage CAPEX and unloading fixed OPEX as 3 % of unloading CAPEX.

[38] Actual Storage and unloading CAPEX is 12.57 $M€_{2016}$ → 13.08 $M€_{2019}$
[39] Storage and unloading fixed OPEX is 0.57 $M€_{2016}$/yr → 0.59 $M€_{2019}$/yr

Reconditioning CAPEX *(M€)*	0.99	1.95[40]	• **Tool 2** has onshore reconditioning unitary capex as 0.99 €/t_{CO2} possibly due to lower equipment cost for reconditioning (e.g. pump costs) • **Tool 1 (2017)** used bottom-up approach to find reconditioning CAPEX to increase the pressure of CO_2 to 200 bar or desired pressure.
Reconditioning OPEX *(M€/yr)*	0.39	0.47[41]	• **Tool 2** has onshore reconditioning unitary OPEX as 0.39 €/t_{CO2} which includes electricity costs. The electricity unitary price is 90 €/MWh. • **Tool 1 (2017)** uses electricity price of 80 €/MWh and cooling water cost of 0.04 €/m^3.

[40] Reconditioning CAPEX is 1.87 M€$_{2016}$ → 1.95 M€$_{2019}$
[41] Reconditioning OPEX in Tool 1 (2017) is 0.45 M€$_{2016}$/yr → 0.47 M€$_{2019}$

Medium Pressure (MP) Ship transport cost comparison between Tool 1 (2017) and Tool 2

Table 21: MP ship transport comparison of Tool 1 (2017) & Tool 2

Cost component	Tool 2 result	Tool 1 (2017) result	Reason

Conditioning CAPEX for MP transport (*M€*)	17.95	32[42]	• **unitary CAPEX**:
			  ○ Tool 1 (2017) → 24 €/($t_{CO2,conditioned}$/yr)
			  ○ Tool 2 → 17.2 €/($t_{CO2,conditioned}$/yr)
			• The scale factors of equipment costs used in Tool 1 (2017) were higher compared to Tool 2.
			• Tool 1 (2017) used 85 % capacity on conditioning (meaning 1.176 MTPA is the capacity of conditioning while the actual conditioned volume is 1 MTPA). Tool 2 uses 100 % conditioning capacity (of 1 MTPA)
			• Tool 2 uses liquefaction CAPEX that has been summarized from list of liquefaction CAPEX values from literature.

[42] The conditioning CAPEX is 30.75 $M€_{2016}$. It is converted to 2019 EURO using the inflation rate of 4.04 % to give 32 $M€_{2019}$

Conditioning Fixed *OPEX* (*M€/yr*)	1.79	1.76[43]	• Tool 2 gives fixed OPEX as 10 % CAPEX/year • Tool 1 (2017) gives fixed OPEX as 6 % CAPEX/year *(uses process overnight factor of 1.09)*

[43] Conditioning CAPEX from Tool 1 (2017) is 30-75 M€$_{2016}$ and process overnight factor is 1.09. So Fixed OPEX = (39.71/1.09) * 0.06 = 1.69 M €$_{2016}$/ yr →1.76 M€$_{2019}$/yr

Conditioning Variable OPEX *(M€/yr)*	7.88	6.90[44]	• Tool 2 uses LNG fuel to provide electrical energy to the liquefaction unit • Tool 1 (2017) used electricity to power the unit and cooling water for the heat exchangers. • Electricity consumption is lower for Tool 1 (2017) than Tool 2 (**Tool 1 (2017)** :76.5 KWh/t_{CO2} **Tool 2**: 83.1 kWh/t_{CO2})
Storage & Loading CAPEX *(M€)*	10.68	18.26[45]	• **Tool 2** assumes that storage size is 20 % higher than the ship size. The ship size selected was 8000 t_{CO2} (around 6900 m^3) The unitary storage CAPEX for Tool 2: **900 €/m^3.** Loading CAPEX: 1.58 €/t_{CO2} • **Tool 1 (2017)** assumes storage size is 25 % greater than ship size of 6510 m^3 (7500 t). Unitary storage CAPEX is **1600 €/m^3.** Loading CAPEX: 2.63 €/t_{CO2}

[44] The cooling water utility cost is 0.04 €/m^3 and electricity is 65.2 €/MWh. Based on that the Variable OPEX is 6.63 M€$_{2016}$ → 6.90 M€$_{2019}$

[45] Actual Storage and loading CAPEX is 17.55 M€$_{2016}$ → 18.26 M€$_{2019}$

Storage & Loading Fixed OPEX *(M€/yr)*	0.50	0.87[46]	• **Tool 1 (2017)** uses 6 % as storage fixed OPEX and loading fixed OPEX as 2 % of loading CAPEX. • **Tool 2** uses storage fixed OPEX as 5 % of storage CAPEX and loading fixed OPEX as 3 % of loading CAPEX.
Ship CAPEX *(M€)*	118.18	87.33[47]	• **Tool 2** compiled ship CAPEX for various ship sizes from many sources and a regression analysis curve was made. Based on that each ship of 8000 t_{CO2} size is 59.09 $M€_{2019}$ (some literature considered First of a kind 'FOK' cost methodology while others considered Nth of a kind cost methodology) • **Tool 1 (2017)** ship CAPEX for 7500 t_{CO2} ship size is 38.5 M€/ship. Tool 1 (2017 uses Nth-of-a-Kind cost methodology which assumes that the technology used is matured. The CAPEX for small size ships are found by performing regression analysis.

[46] Storage and loading OPEX is 0.84 $M€_{2016}$/yr → 0.87 $M€_{2019}$/yr
[47] Original Ship CAPEX for two ships of 7500 t_{CO2} size in Tool 1 (2017) is 83.94 $M€_{2016}$ →87.33 $M€_{2019}$

Ship Fixed OPEX *(M€/yr)*	5.91	2.78[48]	• **Tool 2** gives ship fixed OPEX as 5 % of Ship CAPEX. • **Tool 1 (2017)** gives fixed OPEX that is 5-7 % of the CAPEX. [49]
Ship fuel cost *(M€/yr)*	3.98	2.32[50]	• **Tool 2:** since 8000 t_{CO2} ship size was used due to the limitation of the tool, the fuel consumption of a ship of this capacity is slightly higher than of a ship of 7500 t_{CO2} size. Fuel consumption (LNG) was found for different ship sizes by linear regression analysis of fuel consumptions values from literature. • **Tool 1 (2017)** use unitary fuel consumption provided by a case study. [51]

[48] Ship fixed OPEX given by Tool 1 (2017) is 2.67 $M€_{2016}$/yr → 2.78 $M€_{2019}$/yr
[49] Formula used to calculate Ship annual fixed OPEX= 0.846*(Ship size in $m^3)^{0.315959}$
[50] Ship fuel cost is 2.23 $M€_{2016}$/yr → 2.32 $M€_{2019}$/yr
[51] Formula for calculation unitary fuel consumption (t_{fuel}/t_{CO2}/km) = -4.55421×10^{-11}*(Ship size in m^3)+7.16974×10^{-6}

Harbor fees *(M€/yr)*	2.75	2.86[52]	• **Tool 2:** Harbor fees per round trip was found for different ship sizes by linear regression analysis of harbor fees from literature. Tool 2 calculates that the total number of trips needed by 2 ships of 8000 t_{CO2} size is **125**. • **Tool 1 (2017)** calculates the total number of trips as **139**. Tool 2 report was used to obtain unitary harbor fees for 2 ships of size 7500 t_{CO2}.

[52] Harbor fees given by Tool 1 (2017) is 2.75 $M€_{2016}$/yr → 2.86 $M€_{2019}$/yr

Storage and unloading CAPEX *(M€)*	10.68	18.26[53]	• **Tool 2** assumes that storage size is 20 % higher than the ship size. The ship size selected was 8000 t_{CO2} (around 6900 m^3) The unitary storage CAPEX for Tool 2: **900 €/m^3.** Loading CAPEX: 1.58 €/t_{CO2} • **Tool 1 (2017)** assumes storage size is 25 % greater than ship size of 6510 m^3 (7500 t). Unitary storage CAPEX is **1600 €/m^3.** Loading CAPEX: 2.63 €/t_{CO2}
Storage and unloading Fixed OPEX *(M€/yr)*	0.50	0.87[54]	• **Tool 1 (2017)** uses 6 % as storage fixed OPEX and loading fixed OPEX as 2 % of loading CAPEX. • **Tool 2** uses storage fixed OPEX as 5 % of storage CAPEX and loading fixed OPEX as 3 % of loading CAPEX.
Reconditioning CAPEX *(M€)*	0.92	1.96[55]	• **Tool 2** has onshore reconditioning unitary capex as 0.92 €/t_{CO2} possibly due to lower equipment cost for reconditioning (e.g. pump costs) • **Tool 1 (2017)** used bottom-up approach to find reconditioning CAPEX to increase the pressure of CO_2 to 200 bar or desired pressure.

[53] Actual Storage and loading CAPEX is 17.55 $M€_{2016}$ → 18.26 $M€_{2019}$
[54] Storage and loading OPEX is 0.84 $M€_{2016}$/yr → 0.87 $M€_{2019}$/yr
[55] Reconditioning CAPEX by Tool 1 (2017) is given as 1.88 $M€_{2016}$ → 1.96 $M€_{2019}$

Reconditioning OPEX *(M€/yr)*	0.37	0.44[56]	• **Tool 2** has onshore reconditioning unitary OPEX as 0.39 €/t_{CO2} which includes electricity costs. The electricity unitary price is 90 €/MWh. • **Tool 1 (2017)** use electricity price of 80 €/MWh and cooling water cost of 0.04 €/m^3.

[56] Total reconditioning OPEX (included reconditioning fixed OPEX and electricity cost due to consumption during reconditioning) from Tool 1 (2017) is 0.43 $M€_{2016}$/yr →0.44 $M€_{2016}$/yr (Cost split is annual fixed OPEX of reconditioning is 6% of pump CAPEX per year which gives 0.10 M $€_{2016}$/yr. The electricity consumption cost is 0.32 $M€_{2016}$/yr)

APPENDIX C: Chapter 5 Material

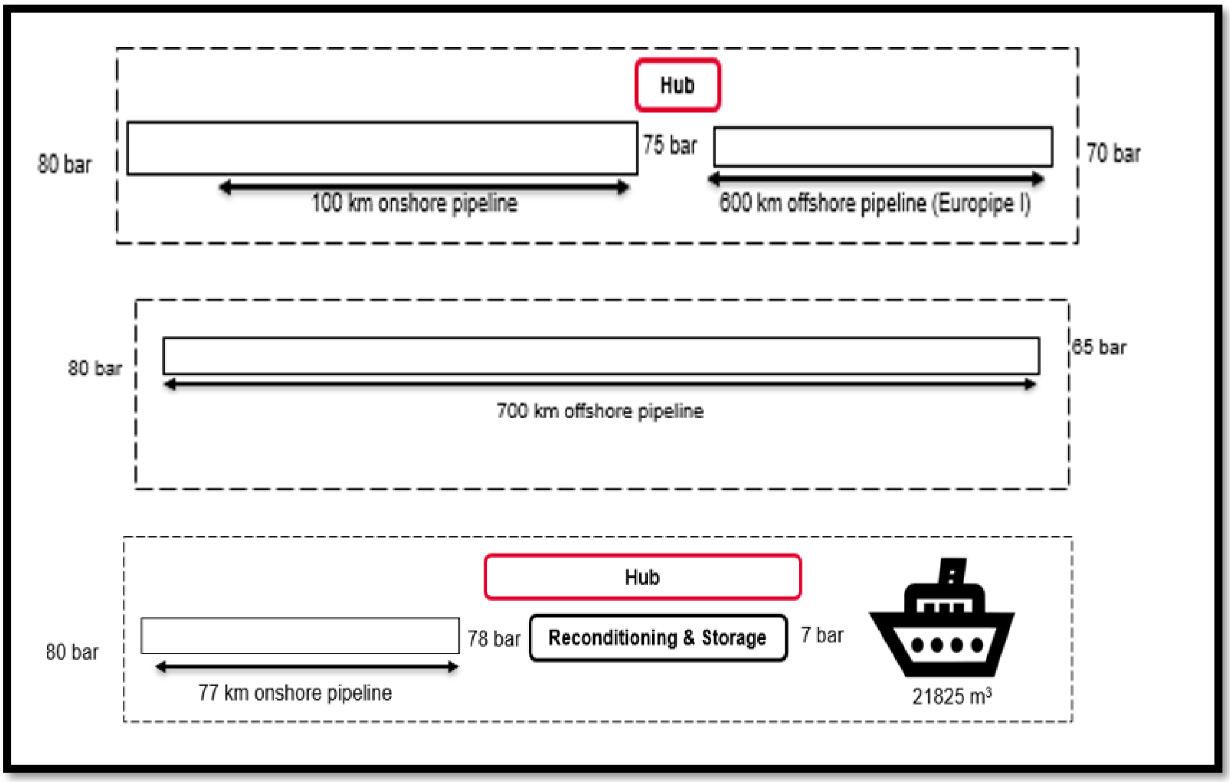

Figure 46: Overall design of transport system of Pipe B (1 MTPA) subcases (a) subcase 1 (b) subcase 2 (c) subcase 3 (top to bottom)

Table 22: Detailed design parameters of Pipe B (1 MTPA) subcases

Pipe B (1 MTPA)	1	2	3
Characteristics	New built- pipeline to hub. Re-use of Pipe B from hub to storage	New built- pipeline to storage	Pipeline to hub (onshore). Ship to storage
Source	Germany		
Distance by ship (km)			630
Ship size (m^3)			21 825
Length of pipeline (km)	100, 600	700	70
Outer diameter (inch)	16 40	16	16
Internal diameter (inch)	15.31 38.74	15.39	15.31
Pipeline thickness (mm)	8.74 15.9	7.92	8.74
Flowrate (MTPA)	1	1	1
Lifetime (years)	25	25	25
Pressure drop (bar)	10	15	2
System boundary pressure (bar)	80		
Inlet pressure of transport system (bar)	80	80	80
Outlet pressure (bar)	70	65	60

Table 23: Base/central case results of Pipe B case from Tool 1 (2012)

Pipe B	Flow rate (MTPA)	Distance (km)	Lifetime (years)	Discount rate (%)	Lifetime costs (M€)	Unitary transport cost (€/t_{CO2})
Subcase 1	16	700	25	8	212	1.2
Subcase 2	16	700	25	8	1657	9.7
Subcase 3	16	700	25	8	1503	8.8

APPENDIX D: Chapter 6 Material

Table 24: Detailed techno-economic and environmental assessment results of comparison between two pipeline diameters (10.75 and 12.75-inch)

Outlet Pressure Pump (bar)	**125**	**100**
Pump size (kW)	721	566
Pump energy consumption (MWh/year)	6319	4957
Pump CAPEX (M€)	1,75	1.55
Pump fixed OPEX (M€)	0.44	0.39
Pump variable OPEX (M€)	8.77	6.88
Pump CAPEX emissions ($kt_{CO2,eq}$)	0.42	0.38
Pump OPEX emissions ($kt_{CO2,eq}$)	2.53	1.98
TOTAL Pump emissions ($kt_{CO2,eq}$)	2.95	2.36
Outer diameter (")	10.75	12.75
Transport capacity (MTPA)	1.5	1.5
Transported volume (MTPA)	1.5	1.5
Internal diameter (")	10.12	12.13
Pipeline thickness (mm)	7.8	7.92
Average fluid velocity (m/s)	0.94	0.67
Inlet pressure pipe (bar)	125	100
Outlet pressure pipe (bar)	80	80
Average pressure drop (bar)	33.9	14.4
Pipeline CAPEX: Material cost (M€)	12.52	15.15
Pipeline CAPEX: Labor cost (M€)	50.18	59.51
CAPEX: Onshore-offshore landfall (M€)	28.9	28.9
Pipeline CAPEX: Miscellaneous (M€)	22.9	25.89
Total pipeline CAPEX (M€)	114.5	129.45
Pipeline Fixed OPEX (M€)	39.37	44.51
Pipeline CAPEX emissions ($kt_{CO2,eq}$)	39.9	45.7
Pipeline OPEX emissions ($kt_{CO2,eq}$)	21.6	24.4
TOTAL Pipeline emissions ($kt_{CO2,eq}$)	61.4	70.1

Table 25: Detailed techno-economic and environmental assessment results for comparison between varying wall thickness of 10.75-inch and 12.75-inch pipeline.

	10.75-inch pipeline			12.75-inch pipeline		
	Base case	**+50% wall thickness**	**-50% wall thickness**	**Base case**	**+50% wall thickness**	**-50% wall thickness**
Outlet Pressure Pump (bar	125	130	115	100	100	100
Pump size (kW)	721	751.92	659.72	566	565.85	565.85
Pump energy consumption (MWh/yr)	6319	6587	5779	4957	4957	4957
Pump CAPEX (M€)	1.75	1.79	1.67	1.55	1.55	1.55
Pump fixed OPEX (M€)	0.44	0.45	0.42	0.39	0.39	0.39
Pump variable OPEX (M€)	8.77	9.14	8.02	6.88	6.88	6.88
Pump CAPEX emissions ($kt_{CO2.eq}$)	0.42	0.43	0.4	0.38	0.38	0.38
Pump OPEX emissions ($kt_{CO2.eq}$)	2.53	2.63	2.31	1.98	1.98	1.98
TOTAL Pump emissions ($kt_{CO2.eq}$)	2.95	3.06	2.71	2.36	2.36	2.36
Transport capacity (MTPA)	1.5	1.5	1.5	1.5	1.5	1.5
Transported volume (MTPA)	1.5	1.5	1.5	1.5	1.5	1.5
Internal diameter (")	10.12	9.76	10.43	12.13	11.89	12.4
Pipeline thickness (mm)	7.8	12.7	4	7.92	11.1	4.37
Average fluid velocity (m/s)	0.94	1.02	0.9	0.67	0.7	0.64
Pipeline design pressure (bar)	160	160	144	130	125	125
Inlet pressure pipe (bar)	125	130	115	100	100	100
Outlet pressure pipe (bar)	80	80	80	80	80	80
Average pressure drop (bar)	33.9	40.8	29.5	14.4	15.9	12.9
Pipeline CAPEX: Material cost (M€)	12.52	20.01	6.51	15.15	21.05	8.45
Pipeline CAPEX: Labor cost (M€)	50.18	50.18	50.18	59.51	59.51	59.51
CAPEX: Onshore-offshore landfall (M€)	28.9	28.9	28.9	28.9	28.9	28.9
Pipeline CAPEX: Miscellaneous (M€)	22.9	24.77	21.4	25.89	27.37	24.21
Total pipeline CAPEX (M€)	114.5	123.86	106.99	129.45	136.83	121.07
Pipeline Fixed OPEX (M€)	39.37	42.59	36.79	44.51	47.05	41.63
Pipeline CAPEX emissions ($kt_{CO2.eq}$)	40	48	34	46	52	39
Pipeline OPEX emissions ($kt_{CO2.eq}$)	22	23	20	24	26	23
TOTAL Pipeline emissions ($kt_{CO2.eq}$)	61	71	54	70	78	62