Project:

CO2LOS
CO2 Logistics by Ship Phase II

Document Title:

CO2LOS II - Final Report with toolbox for CCS logistics

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SUMMARY

This report summarizes the work performed in the CO2LOS II project. A total of 13 work package reports has been issued throughout the project, all documenting topics within the field of CO_2 logistics by ship as a part of a CCS (Carbon Capture and Storage) chain. Capture and storage are outside the battery limits for the project. A flowchart visualising the different project parts is provided in Part I of the report. Summaries from each of the work packages is presented in Part II of the report. Finally, in Part III of the report, CAPEX and OPEX cost for a selection of CCS logistics cases has been estimated. Long and short depreciation time has been used to compare the cost development where relevant.

The project has focused on conceptual engineering of the different parts of the logistics chain covering a wide variety of choices, typically such as if the unloading from the ship is done to a shore terminal or at an offshore location. The intention has been to fill up a toolbox to be used for future CCS logistics.

Some of the items covered in the project are:

- A design basis identifying and setting the parameters at the battery limits of the project
- Discussion and selection of CO_2 transport pressure
- Development of a low pressure ship tank for CO_2, design pressure 7 barg
- Liquefaction plant concept
- Selection and conceptual design of intermediate storage tanks
- Floating liquefaction and storage concept
- GHG (Green House Gas) emissions from the CCS logistics operation
- CO_2 tank BoG (Boil off Gas) calculations
- Development of five ship concepts for different shore to shore ship logistics
- Development of three scenarios for offshore unloading
- Offshore unloading scenarios selection tools
- CO_2 capture onboard the ship
- Evaluation of possible return cargo and alternative use of a CO_2 ship
- Database tool containing inland waterways and CO_2 emitters in continental Europe
- Benchmarking the Northern Lights project

It is not possible, neither has it been the target of the project to find the one and only optimal technical solution for a CCS ship logistics chain. The selections will have to be adjusted when a firm CCS project is developed with decisions of volumes, export and import site, transport pressure, location, and characteristics of the reservoir, etc. Acknowledging this, the methodology used for development of the solutions, including logistics, simulations, calculations, analysis, results from discussion with partners and vendors, and literature studies are as important as the developed concepts. There are however some more general findings that should be noted from the project work:

- Low pressure is a feasible alternative to the medium pressure normally used for CO_2 ship transport
- Substantial GHG reductions must be implemented in future ship design to achieve the goals of the international community
- Liquefaction CAPEX and OPEX is a major part of the logistics chain cost

INTRODUCTION

Carbon Capture and Storage is addressed by IEA as one of the key technologies of reaching the Paris agreement 2°C goal. In the IEA 2°C scenario 1 gigatonnes/y CO_2 will need to be captured by 2030 ramping up to 5 gigatonnes/y in 2045. This will require huge logistic operations. CCS/CCU transport has up to now been based on pipelines. Transport of CO_2 by ship represents an alternative when pipelines are too expensive due to distance, volume, and depreciation period. Food grade CO_2 has been transported with ships for decades, but these volumes are rather small compared to the planned CCS projects.

The project focuses on the transport part of the CCS chain assuming ship transport with liquefied CO_2. CO2LOS II includes pre-treatment (liquefaction) needed before ship transport, but not the capture of CO_2 from source, neither is the reservoir part of the project, ref. Figure 1. Both land based delivery and offshore unloading are being addressed.

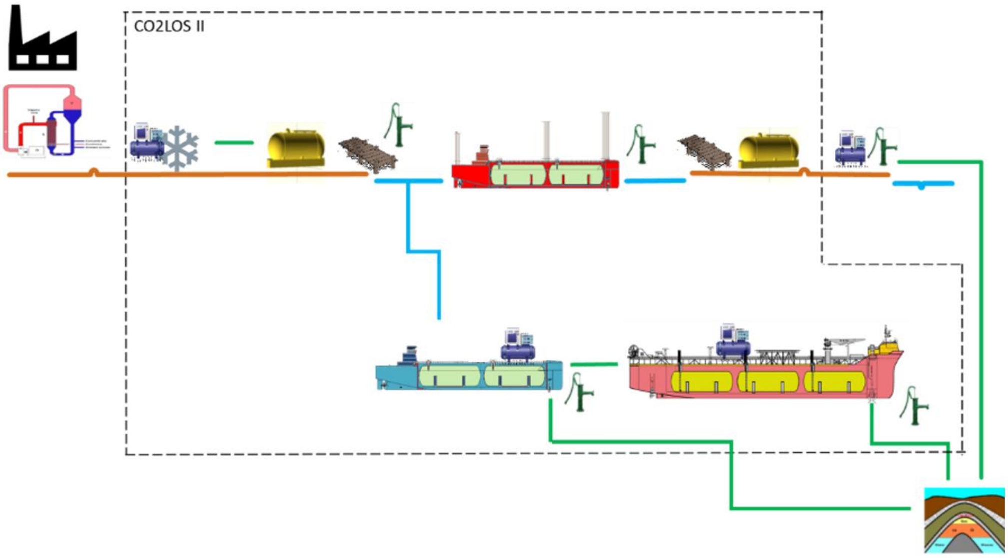


Figure 1 The CO2LOS II project battery limits

The scope of the CO2LOS II (CO_2 Logistics by Ship Phase II) project is to reduce the cost of CO_2 ship transportation by utilizing new technology and investigate optimization possibilities in the logistic chain.

This document is the public version of the final report documenting the CO2LOS II project. The report serves as a toolbox summarizing various engineered conceptual technical solutions with an estimate of when these solutions may be applicable for CO_2 transport.

The technical solutions will have to be adjusted when a firm CCS project is developed with decisions of volumes, export and import site, transport pressure, location, and characteristics of the reservoir, etc. Acknowledging this, the methodology used for development of the solutions, including logistics, simulations, calculations, analysis, results from discussion with partners and vendors and literature studies are made an important part of the toolbox.

PART I - THE TOOLBOX

The CO2LOS II toolbox, is described by a schematic project overview, ref Figure 2. WP (Work Package) titles are clickable for fast forwarding to relevant sections of the report. To later return to this page, click the CO2LOS logo top right on any page.

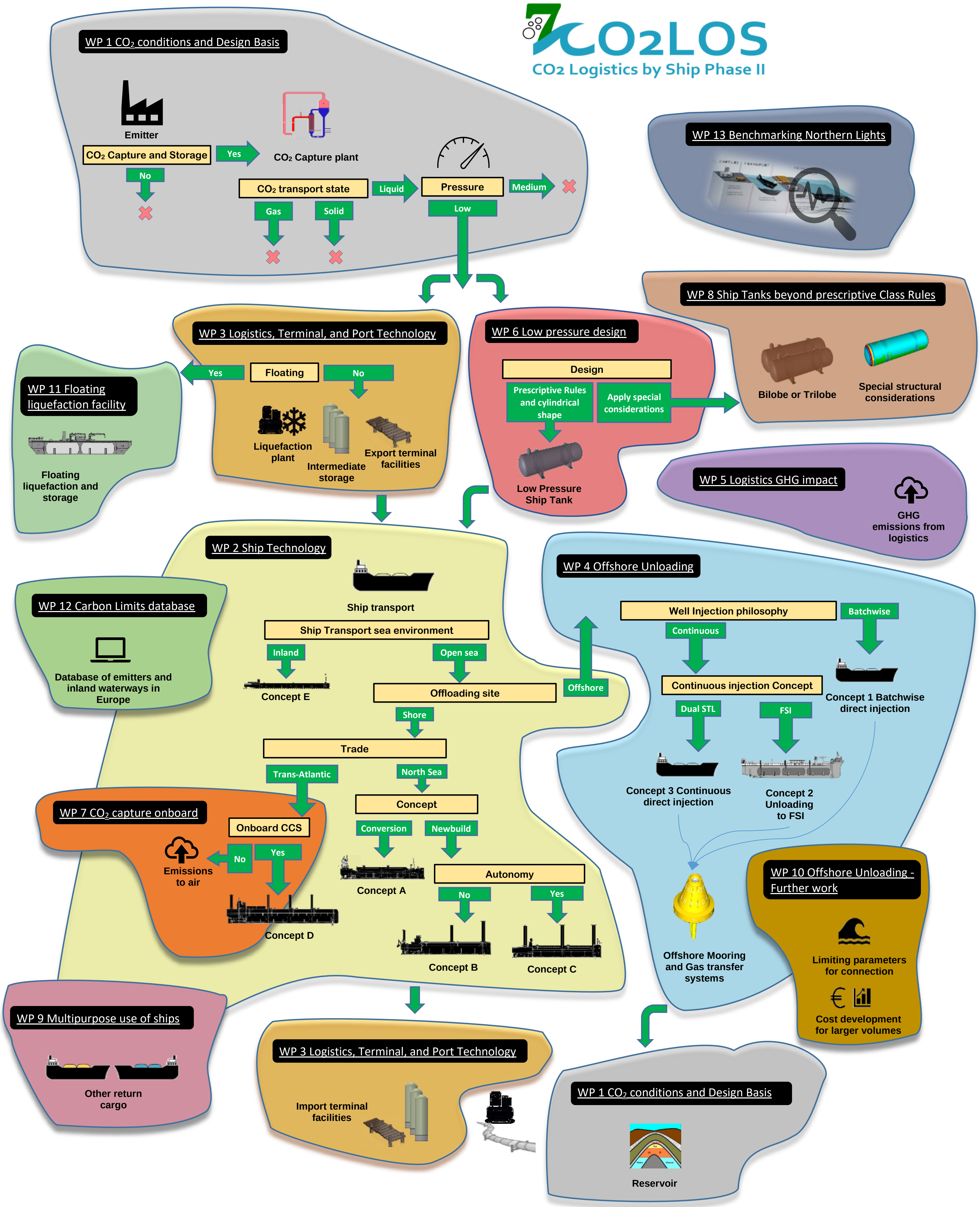


Figure 2 The CO2LOS II toolbox

1 TOOLBOX DESCRIPTION

The CO2LOS II project is documented in detail through 13 work package reports. In addition, the final report is issued for the purpose of summarizing the project and providing a tool to be used for accessing the project information. A public version of the final report (this report) is issued to provide a publishable project summary.

The final report serves as a toolbox for CCS logistics by ship, containing a summary of various engineered conceptual technical solutions, associated high level costs and estimate of when these solutions may be applicable for CO_2 transport.

The technical solutions will have to be adjusted when a firm CCS project is developed with decisions of volumes, export and import site, transport pressure, location, and characteristics of the reservoir, etc. The methodology used for development of the solutions, including logistics, simulations, calculations, analysis, results from discussion with partners and vendors and literature studies are an important part of the toolbox. These tools are in general not available in the final report but are documented in the separate work package reports.

The CO2LOS II project covers a wide range of aspects connected to CCS by use of ships. A given CCS project will have to make certain choices when defining the path of the project. Figure 2 CO2LOS II toolbox is an overall visualization of the projects different work packages, how they are connected, and which choices are made to reach the engineered concepts described in the reports.

2 HOW TO USE THE TOOLBOX

The toolbox is the natural starting point for multiple interests and scenarios related to CCS, some examples of how to use the toolbox are given below:

2.1 Example 1 – GHG Impact

If the item of interest is the results of the logistics GHG impact analysis, a click on the WP 5 text ① will take the reader to the result summary included in the final report ②. If further information is needed such as detailed analysis results, sensitivities, methodology, cost etc the full work package report should be visited ③, ref (1). This report is not publicly available.

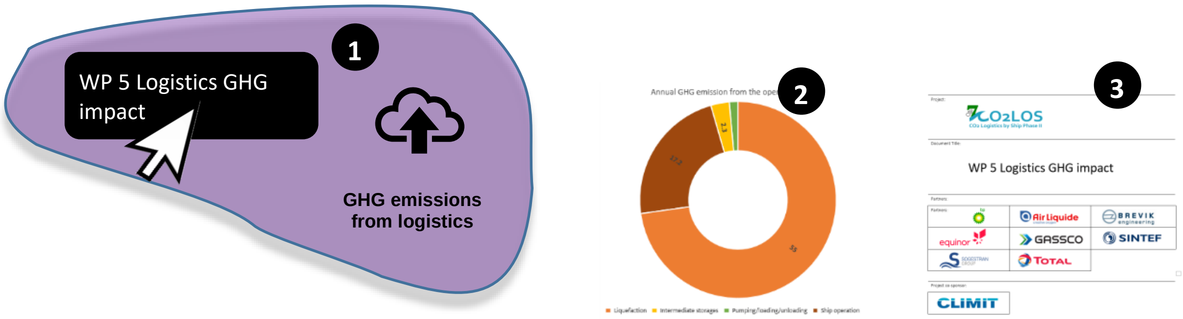


Figure 3 Toolbox example 1

2.2 Example 2 – Developing a CCS scenario

Assuming an emitter consider developing a CCS chain by use of the toolbox, the following decisions as outlined in the toolbox would be relevant:

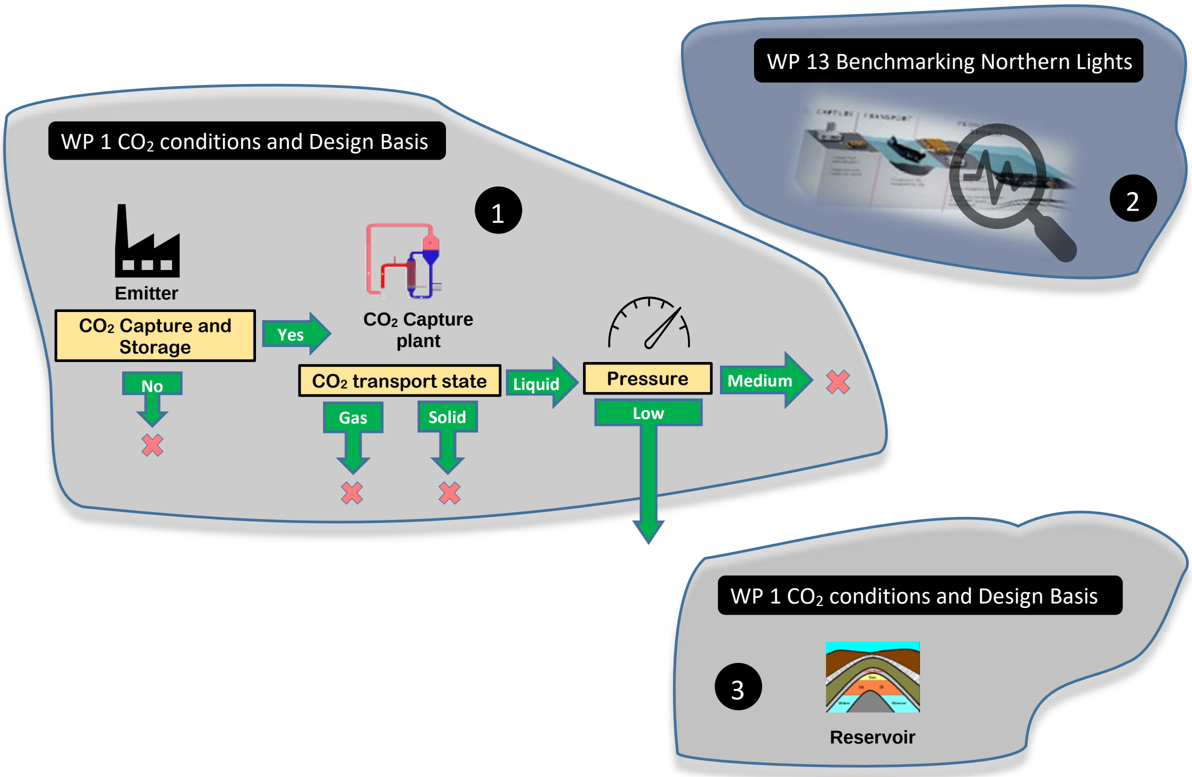


Figure 4 Toolbox example 2a

❶ Is capture feasible, the volumes and the method of capture. Capture is not a part of the CO2LOS II project, but the location of the plant, the captured volumes and the state of CO_2 delivered from the capture plant is needed as an input to the next CCS steps such as selection between pipeline and ship transport and as a consequence, in which form the CO_2 shall be transported. With the selection of ship transport, a liquid state is the only form with a sufficient TRL to be used in the concepts developed for the CO2LOS II project.

Finally, the transport pressure of the liquefied CO_2 should be decided. A pressure study is made in ref (2).

❷ Benchmarking on pressure selection. Only concepts for low pressure has been developed in CO2LOS II, however benchmarking on the medium pressure chosen for the Northern Lights project ref (3) is done in WP 13, ref (3).

❸ Selection of the reservoir itself is not a part of the CO2LOS II project, however location, capacity, and type of receiving facility (onshore, offshore, etc) are important boundary conditions that needs to be decided in an early planning phase.

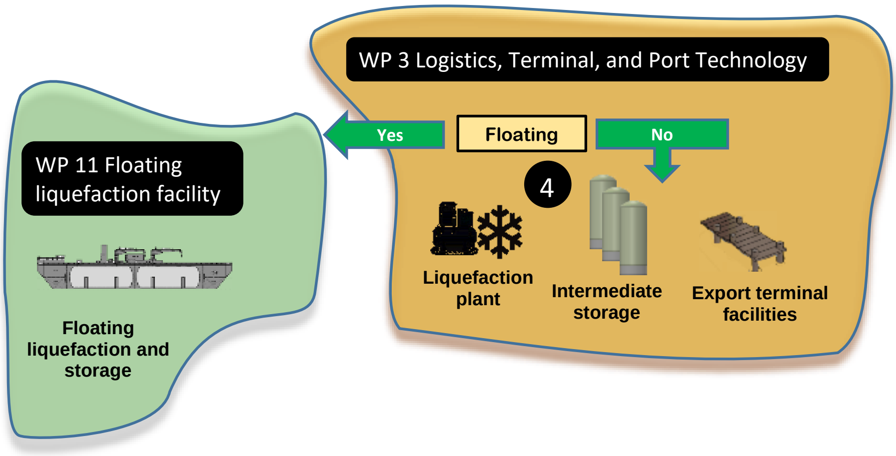


Figure 5 Toolbox example 2b

❹ Type of export terminal. Both a land based terminal, floating storage and floating storage and liquefaction have been studied in WP 3 and WP 11, ref (4) and (5), respectively. The floating concepts are all assumed close to shore in a sheltered location. Relevant selections are further detailed in Figure 11.

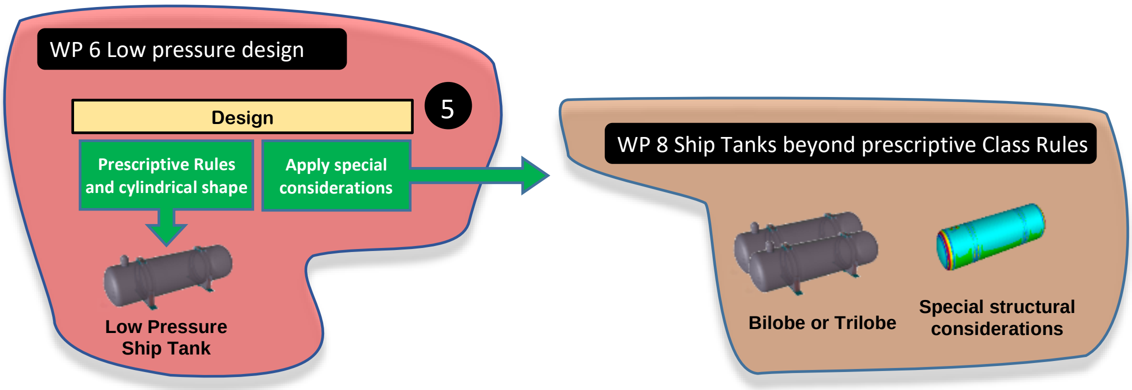


Figure 6 Toolbox example 2c

❺ Design of the low pressure ship tank. If the design is made within the prescriptive Class Rules and the IGC code, a relatively cheap tank with straight forward manufacturing and off the shelf materials can be expected as described in WP 6, ref (6). By challenging the rules, benefits on size and shell thickness may be achieved. This is further discussed in WP 8, ref (7). Relevant selections are further detailed in Figure 18.

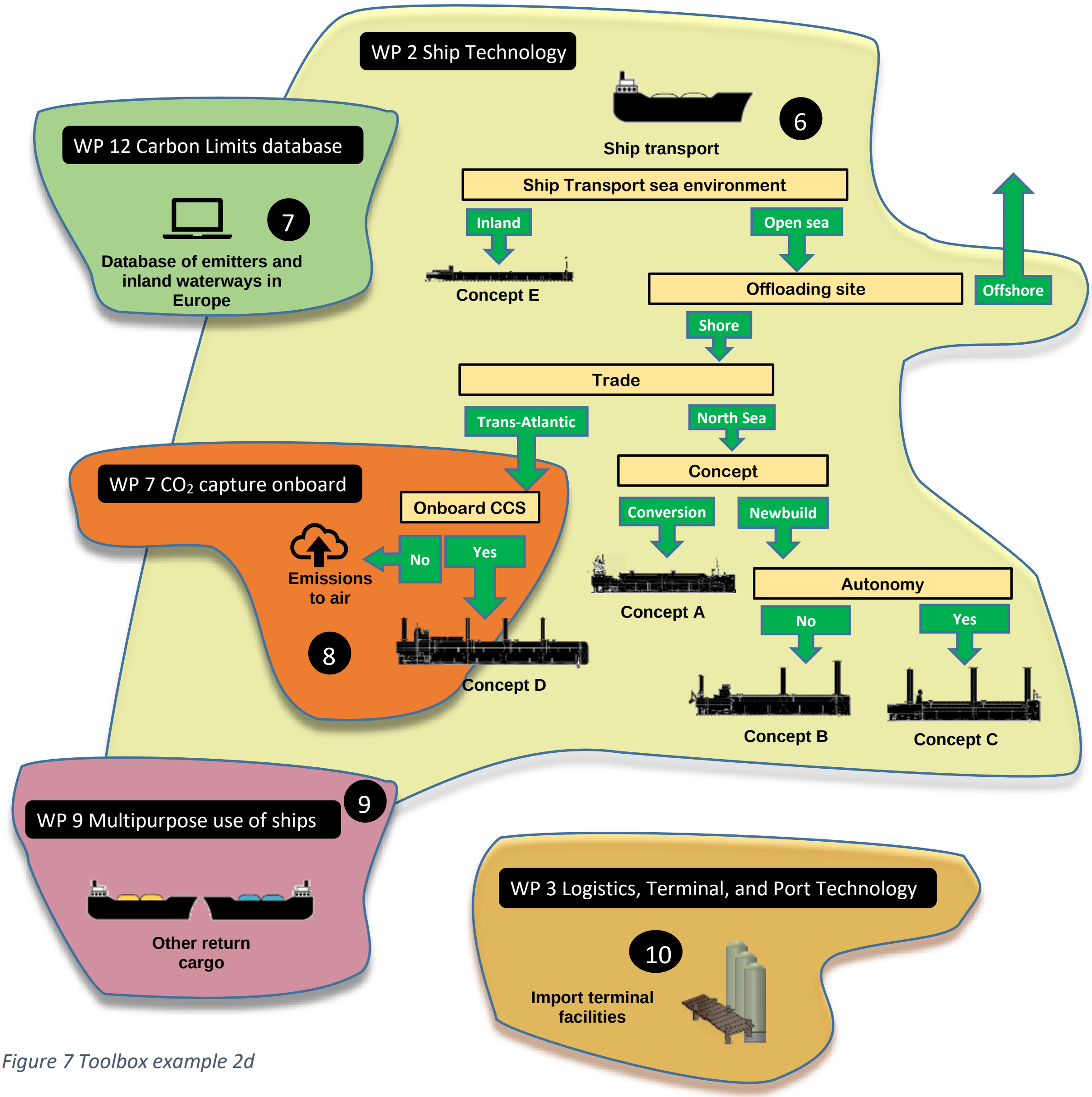


Figure 7 Toolbox example 2d

❻ Selection of ship concepts. In WP 2, ref (8) the ship concepts developed for shore to shore trade has been defined. Further selections such as inland or open sea voyage, trading area, conversion or newbuild, autonomy, etc will provide a choice of concept.

❼ Assuming an inland CO_2 source, the tool in WP 12, ref (9), could be used to find the best inland waterway for the transport.

❽ Implementation of CO_2 capture and storage on board. This has been considered for the large ship Concept D in WP 7, ref (10).

❾ Return cargo. If relevant return cargoes exist on the chosen trade route, a ship design allowing for this could be considered. Relevant return cargoes are identified in WP 9, ref (11).

❿ Selection of import facility (not applicable for offshore unloading). The Northern Lights facilities at Kollsnes was selected as a base case import terminal facility in WP 3, ref (4).

If offloading site offshore is selected in Figure 7, further selections should be made based on WP 4, ref (12).

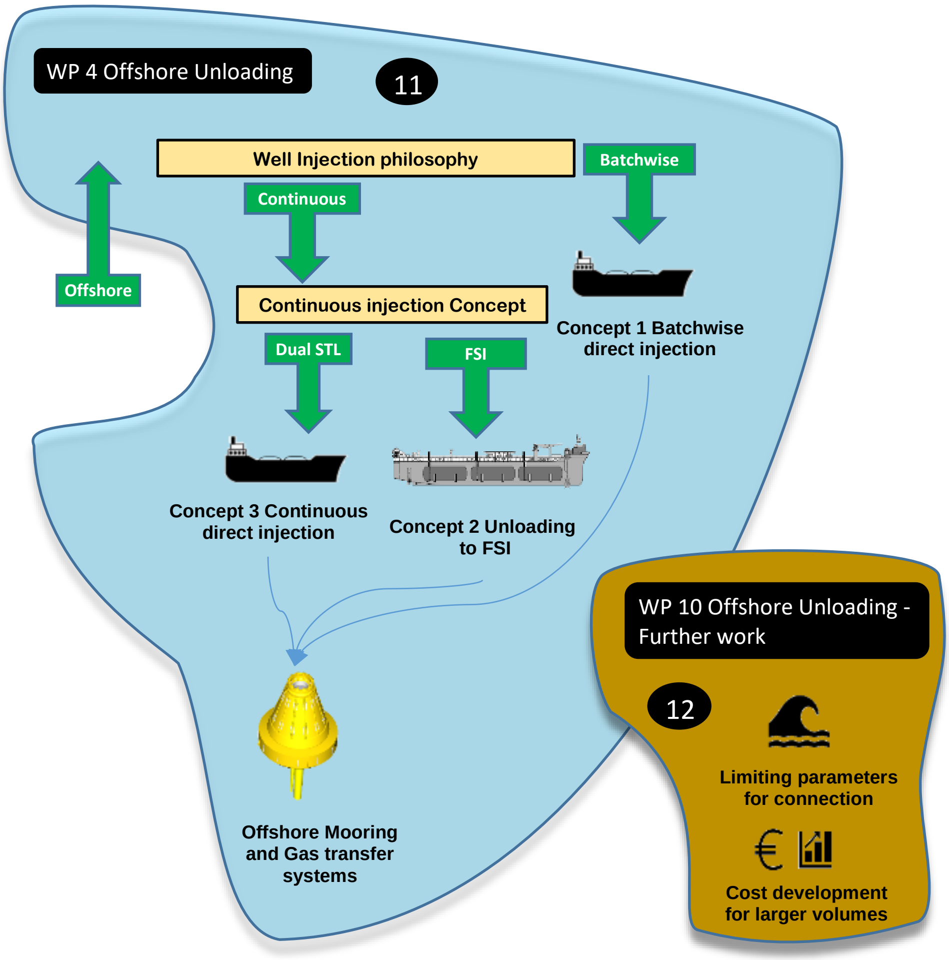


Figure 8 Toolbox example 2e

⑪ Three specific concepts of Offshore Unloading have been developed. To select between the concepts the first choice is if to apply batchwise or continuous injections. For continuous injection either a dual offloading system with overlap of arriving vessels or a permanent storage unit (FSI) could be selected

⑫ If other ship and FSI sizes than those developed in WP 4 is needed due to larger amounts of CO_2, larger sizes with associated cost is developed in WP 10, ref (13).

PART II – PROJECT RESULTS

1 WP 1 CO_2 CONDITIONS AND DESIGN BASIS

WP1 provides the basis of design to be used in the CO2LOS II project. Items discussed in WP 1, ref (14) are outside the boundaries of the project itself but are needed as input for the other work packages. Typical items are amount of CO_2 captured and well injection capacity.

The project focuses on the transport part of the CCS chain assuming ship transport with liquefied CO_2. CO2LOS II includes pre-treatment needed before ship transport, but not the capture of CO_2 from source. Both land based delivery and offshore unloading are being addressed.

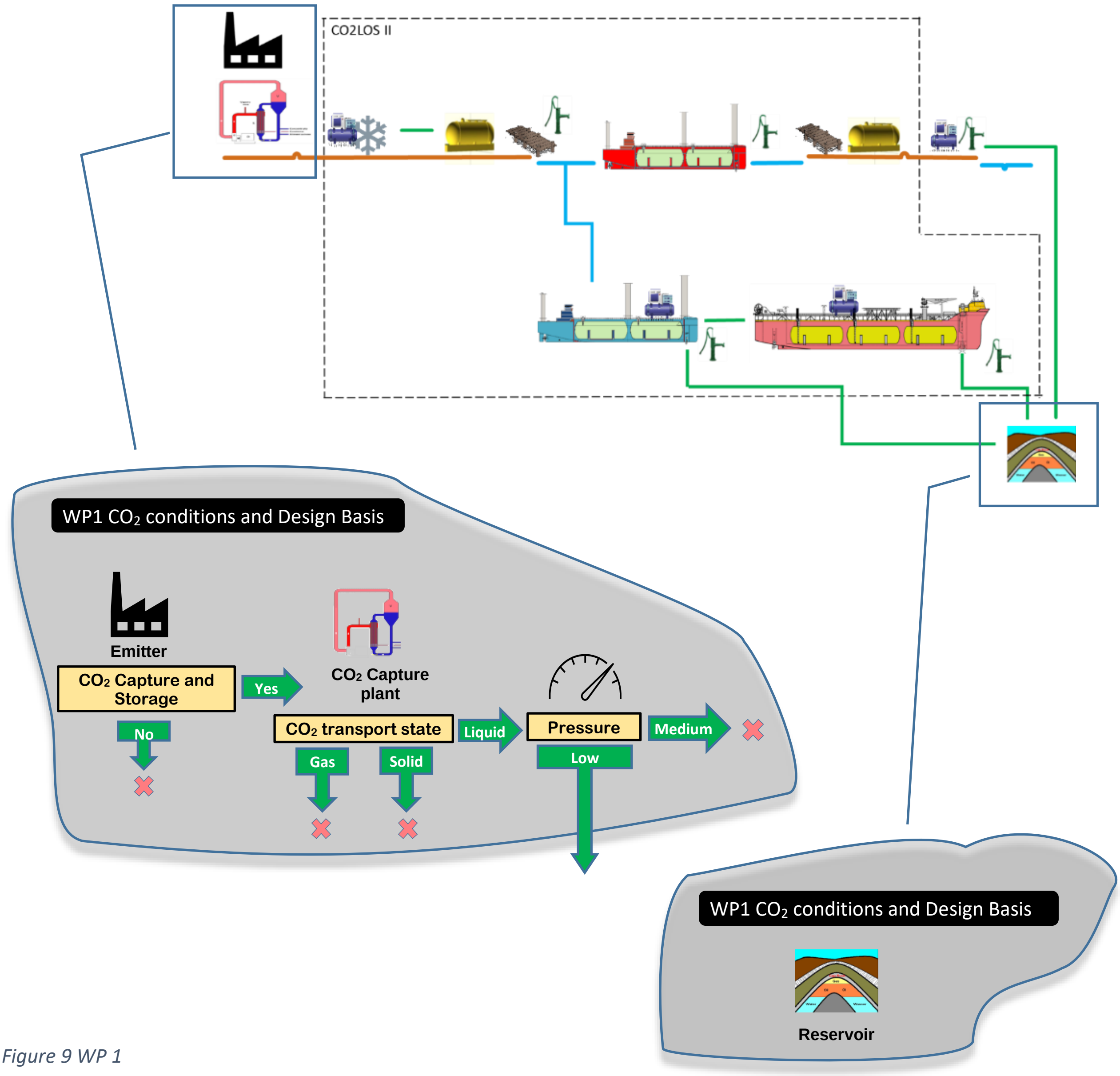


Figure 9 WP 1

1.1 Pressure Study

For the purpose of ship transport, the pressure of the transported CO_2 may be divided in three pressure segments:

1. Low pressure
2. Medium pressure
3. High pressure

CO_2 only exists as either a solid or gas at atmospheric pressure and therefore requires pressurisation to reach a liquid state, ref. Figure 10.

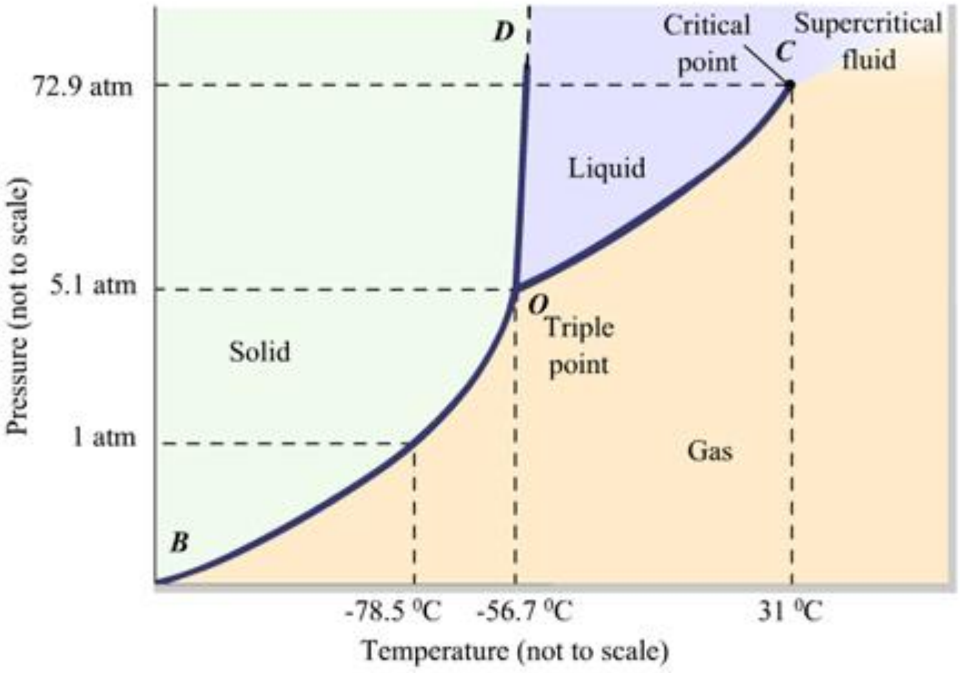


Figure 10 CO_2 Phase diagram, ref. (15)

Assuming liquid phase of CO_2 will be the preferred state, a certain temperature is required depending on the chosen pressure. Typical low, medium, and high-pressure state with corresponding temperature and density is listed in Table 1.

Table 1 CO_2 transport pressure

Segment	Typ. operating pressure	Temperature	Density
Low pressure	6 barg	-50°C	1.155 t/m^3
Medium Pressure	15 barg	-28°C	1.076 t/m^3
High Pressure	70 barg	0°	0. 97 t/m^3

In this study only low and medium pressure condition is discussed as high pressure condition would require a large number of small tanks at a high cost, ref (12). Shipping of CO_2 at medium pressure is proven technology and is used daily in the food and beverage industry. These ships are rather small compared to the volumes needed for CCS. No CO_2 ship is currently in operation with CO_2 at low pressure.

In general, low pressure transport condition will increase the cost of liquefaction and conditioning because the energy consumption is higher compared to medium pressure conditions. On the other hand, intermediate storage, both on export and hub site, and shipping is associated with lower cost for the low pressure condition. The transport and storage efficiency are generally higher for low pressure condition.

Hydrate formation is avoided with the current water content limit of 30 ppmv. More research regarding water content limit for CO_2 transport is needed. The risk of dry ice formation is higher for the low pressure condition due to operation closer to the triple point.

A higher degree of pressure control is needed for the low pressure transport condition as it operates closer to the triple point, however manual and automatic safety valves (double set) should be enough. In case of unwanted release of liquid CO_2 to the atmosphere the effect is largely the same regardless of pressure condition.

Comparison between low and medium pressure for the different steps in the logistics chain is performed in more detail in the following tables.

Table 2 Elements that are relevant for liquefaction.

Liquefaction	MP, 15 barg	LP, 6 barg
Flash	70 barg to 15 barg – 34.4% flash 19 barg to 15 barg – 0% flash	70 barg to 6 barg – 43.8% flash 19 barg – 6 barg – 13.7% flash
Heel	4% heel	1.6% heel
Material	Moderate minimum temperature at approximately -28°C.	Lower temperature at appx -50°C may result in need for higher quality materials and increase the cost. Ref. WP6.
Energy consumption	The smaller flash volume compared to LP reduces the compressor load.	Higher energy consumption than for MP due to the lower temperature and increased flash (increased compression work). The higher compression work increases the energy cost.

Table 3 Elements that are relevant for intermediate storage.

Intermediate storage	MP, 15 barg	LP, 6 barg
Storage pressure	According to structural calculations based on the IGC code and assuming same material and tank shell thickness, the maximum diameter is approximately half of what is achievable for the LP condition, i.e. there is need for more tanks to be able to store the same amount of CO_2. Ref. WP6 and WP8. The need for smaller tanks increases the number of tanks and from this an increase in cost compared to the LP condition.	
CO_2 density	Liquid CO_2 – 1.060 t/m^3 The density is lower than for the LP condition, resulting in less efficient storage	Liquid CO_2 – 1.153 kt/m^3 The higher density increases the storage efficiency by around 10% compared to MP.
Material	MP allows for utilisation of a higher material tensile strength resulting in reduced scantlings but more expensive materials	LP requiring a minimum temperature of approximately -50°C may result in need for higher quality materials and increase the cost. Ref. WP 6.
Dry ice formation		The margins for formation of dry ice are smaller for the LP condition
Hydrate formation		Increased risk of hydrate formation
Boil-off	CO_2 boil-off can be returned to the liquefaction plant for conditioning.	Same as for MP.

Table 4 Elements that are relevant for Loading and Unloading

Loading and Unloading	MP, 15 barg	LP, 6 barg
Pumps, loading arms and hoses		Low temperature hoses are available today, therefore, it is not expected that this should be an issue. In addition, the loading and unloading capacity of the ship is expected to be the same.

Table 5 Elements that are relevant for the ship transport

Ship transport	MP, 15 barg	LP, 6 barg
Transport pressure	Ref. Intermediate storage: maximum diameter is approximately half of what is achievable for the LP condition, i.e. there is need for more tanks to be able to transport the same amount of CO_2. This will have a negative impact on ship size, weight and cost compared to LP.	
CO_2 density	Ref. Intermediate storage	
Heel	Approximately 4% returns with the ship, reducing the transport capacity	1.6 to 2.0% returns with the ship, reducing the transport capacity less than for MP
Transport efficiency	Lower transport efficiency than LP.	The higher density and smaller heel results in approximately 10% higher transport volume of CO_2 for the same tank volume.
Material	Ref. Intermediate storage	
Hydrate formation		Increased risk of hydrate formation
Dry ice formation		The risk of dry ice formation is higher for the LP condition due to operation closer to the triple point
Safety margin	Ship operates at pressure well above the triple point, still safety measures are in place to handle unwanted changes in operating conditions.	Ship operates at pressures close to the triple point, which will require sufficient safety measures (control system and valves) in place ensure safe operation.
Boil-off	Proper tank insulation as well as relief valves (both manually operated and safety valves) will ensure safe operation.	Same as for MP, but safety margin is smaller and accurate pressure control becomes important [5]. Will require more insulation than MP to avoid excessive boil off.

Table 6 Elements that are relevant for conditioning before pipeline and injection

Conditioning before pipeline and injection	MP, 15 barg	LP, 6 barg
Heating and compression		The LP condition has a higher heat and compression demand than the MP condition.

Choice of pressure to be used in the project is made in chapter 1.2 Design basis.

1.2 Design Basis

The pressure temperature and purity values listed in Table 7 and Table 8 apply as input from the part of the CCS process (capture) prior to the battery limits of CO2LOS II.

Table 7 Base Case Parameters

Parameter	Value
CO_2 delivery pressure from Capture site	0.7 barg
CO_2 delivery temperature from Capture site	25°C

The CO_2 impurity limits listed in Table 8 apply. These values are as for the Norwegian full-scale CCS-project (Longship).

Table 8 CO_2 impurity limits

Compounds	Value
H_2O ppmv	≤30
NOx, SOx, O_2 ppmv	≤10
CO ppmv	≤100
H_2S ppmv	≤9
H_2 ppmv	≤50
Hg ppmv	≤0.03

Based on an evaluation of the items listed in chapter 1.1, a cost saving potential is identified by using low pressure compared to medium pressure. Despite of a lower TRL level, narrow operating window and need for more conditioning, low pressure is selected as the base case for the project. Low pressure is believed to best fit the project scope of reducing the cost of CO_2 ship transportation by utilizing new technology and investigate optimization possibilities in the logistic chain. This is achieved by allowing for larger low pressure tanks with reduced scantlings and weight compared to medium pressure tanks. The operational and design values listed in Table 9 apply.

What are considered likely scenarios for CCS by ship, has been developed.

1.2.1 North Sea case including Offshore Unloading case

The North Sea case is described in Table 9. The import port is assumed to be a future phase II at the Northern Lights terminal allowing for receipt of low pressure CO_2 carried by vessels exceeding 130 m length.

A North Sea Case with offshore unloading in the area of the Norwegian Gullfaks oil field is described in Table 10. The Statfjord Group Aquifer in this area is listed as one of several feasible locations for storage of CO_2 in the NPD CO_2 Storage Atlas NCS (16). This area is considered a conservative choice of location for CO_2 offshore unloading, due to the harsh weather conditions. The offshore unloading case investigates both the option with unloading to an FSI (Floating Storage and Injection unit) and direct injection to the reservoir from the ship. Both batchwise and continuous injection are considered. Parameters related to continuous injection are listed in Table 10.

Table 9 North Sea Case, applicable for Ship Concepts A, B and C

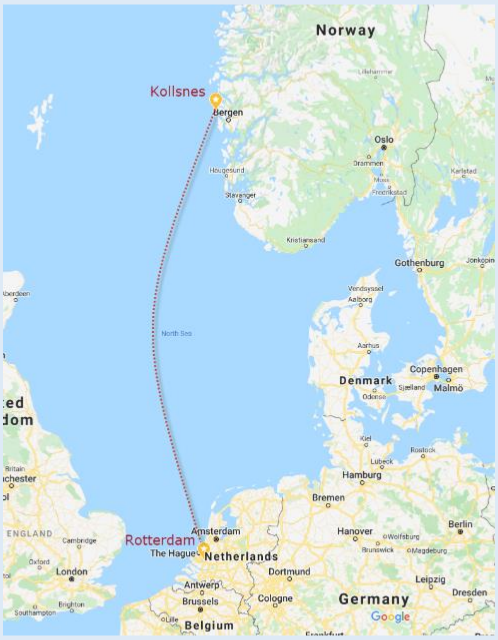
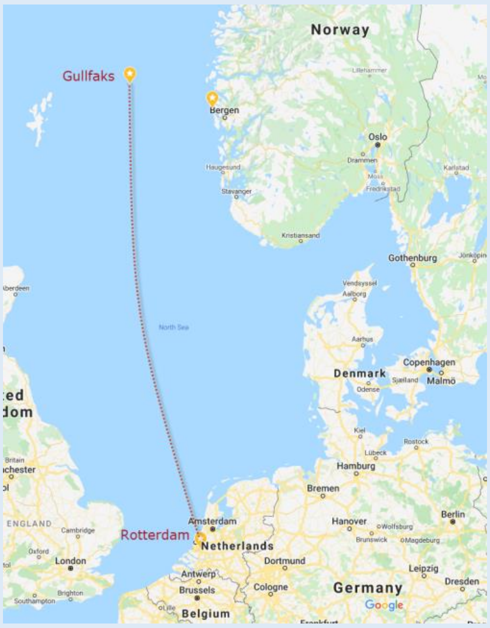
North Sea base case		
	Export port	Rotterdam
	Import port	Kollsnes
	Transport Volume	2.0 Mt/y
	Sailing distance one way	540 nmi
	Ship draught fully loaded	Max 8.5 m
	Loading and Unloading rate per tank	600 t/h
	Transport pressure (operational)	6 barg
	Transport Temperature (operational)	-50°C
	Transport Pressure (design)	7 barg
	Transport Temperature (design)	-55°C
	Shore Storage capacity	1.0 x Ship

Table 10 Offshore Unloading Case, applicable for Offshore Unloading Concepts 1, 2 and 3

North Sea case with Offshore Unloading*		
	Unloading site	Gullfaks
	CO_2 delivery Pressure to reservoir	70 barg
	CO_2 delivery Temperature to reservoir	0°C
	Water depth	200 m
	Well capacity	1.0 Mt/y
	Well injection rate (average)	114 t/h
	Well injection rate (max)	200 t/h
	Continuous well injection minimum rate	5%
	Loading and Unloading rate (max)	3000 t/h
	Shore Storage capacity	1.5 x Ship

*North Sea Base Case values apply unless noted otherwise

1.2.2 Trans-Atlantic case

The trans-Atlantic case is described in Table 11 . The ship transport will be from shore to shore from Rotterdam to the Gulf of Mexico (Port Arthur). As a benchmark also a medium pressure logistics case is considered in WP 2, ref (8).

Table 11 Trans-Atlantic case, applicable for Ship Concept D

Trans-Atlantic case		
	Export port	Rotterdam
	Import port	Port Arthur
	Transport Volume	3.0 Mt/y
	Sailing distance one way	5 000 nmi
	Ship draught fully loaded	na
	Loading and Unloading rate	6 000 t/h
	Transport pressure (operational)	6 barg
	Transport Temperature (operational)	-50°C
	Transport Pressure (design)	7 barg
	Transport Temperature (design)	-55°C
	Shore Storage capacity	1.0 x Ship

1.2.3 Estuary and Inland waterways Case

The case of a self-propelled barge for CO_2 transport operating as a feeder to a central hub in the ARA, Zeebrugge and up the Rhine to Duisburg area is described in Table 12. Estuary Class for coastal trade Belgian coast and BV Class Rules to be applied.

Table 12 Parameters for Estuary and Inland Waterways, applicable for Concept E

Estuary and Inland waterways case		
	Max draft	3.5 - 4.0 m
	Max air draft	9.1 m
	Max length	135.0 m
	Max breadth	22.8 m
	Sailing distance (appx)	150 nmi
	Max tank size	1000 m^3
	Max tank filling	95%

1.2.4 Cost Assumptions

There are several assumptions for the cost calculations in this project. General key figures for the project are listed in Table 13.

Table 13 Key figures for Cost calculations

Parameter	Value
Reference year for cost level	2018
Currency	EUR (€)
Escalation	CPI in Eurostat
Exchange rate NOK/€	9.5
Exchange rate NOK/USD	7.5

Specific cost assumptions for the cost estimation of the land-based facilities are listed in Table 14.

Table 14 Assumptions for Cost calculations of the land based facilities

Assumption
If not specified, Nth of a kind is assumed
Generic location means Rotterdam location
Design lifetime for land plant: 25 (2 year for construction and 23 years operation)
The liquefaction and intermediate storage will be treated as an extension to the existing plant
Purchase of land is calculated as a separate cost
No additional cost for offices, canteen or other secondary buildings are foreseen
Operational time same as for emission source, and will be assumed 8300 hours operating time per year
For generic calculations, the liquefaction and intermediate storage are assumed to be outside Ex area

Typical utility prices for the land based facilities are given in Table 15.

Table 15 Assumptions for Cost calculations of the land based facilities

Utility	Value
Cost of Electric Power [€/kWh]	0.055
Cost of Cooling Water [€/m^3]	0.02

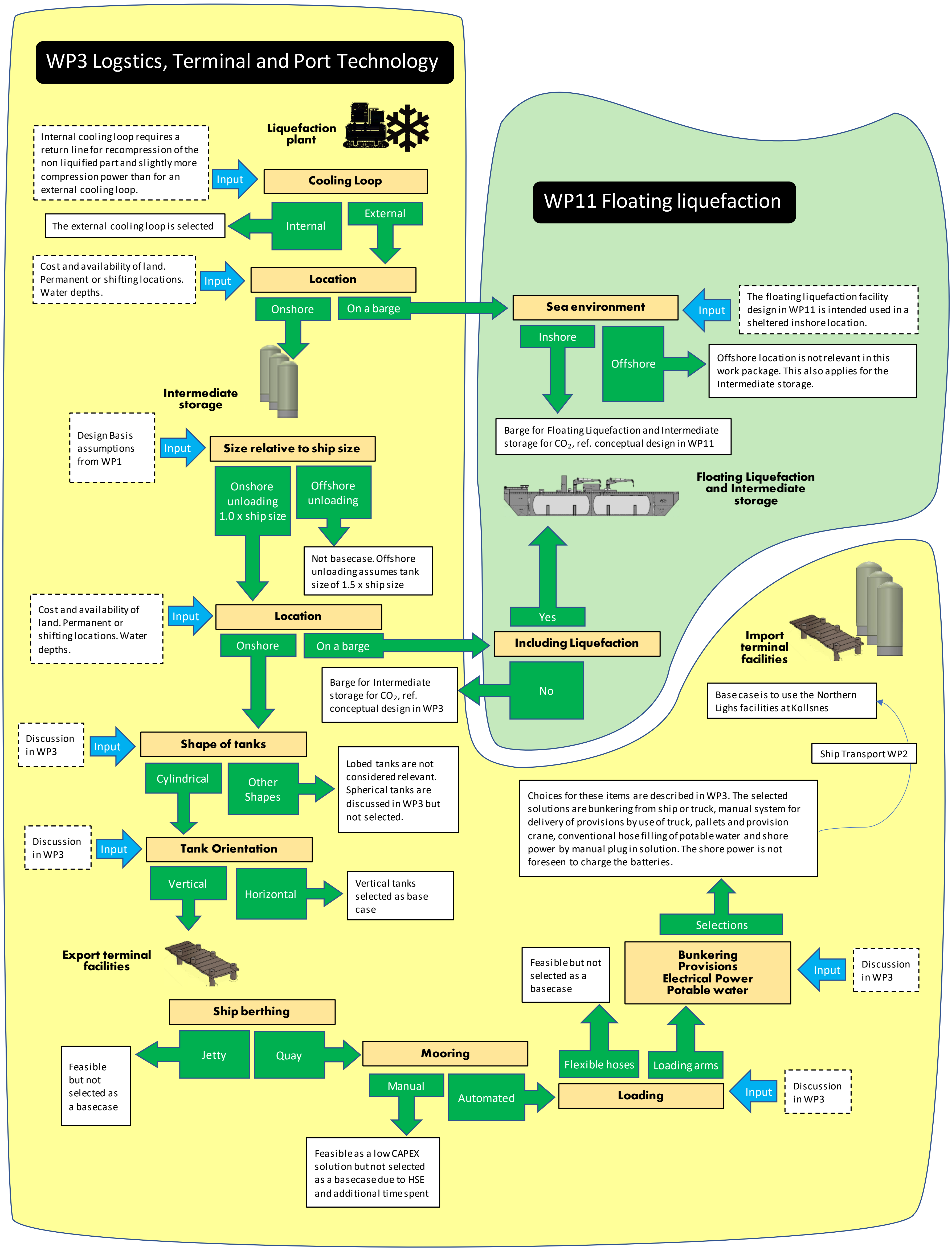
Specific cost assumptions for the cost estimation of the Offshore Unloading case is listed in Table 16.

Table 16 Assumptions for offshore unloading

Parameter	Value
Assumed FSI lifetime:	25 years
Assumed Ship lifetime	20 years

2 WP 3 LOGISTICS, TERMINAL, AND PORT TECHNOLOGY

This work package is centred on logistics, terminal and port technology and contains a detailed investigation into the export terminal of a CCS chain. Important elements included are liquefaction, intermediate storage tank facility, port facility and interface between onshore terminal and ship. The premise of the investigation is the North Sea case, ref. Table 9. In Figure 11 an extension of the toolbox in Figure 2 is presented. Here WP 3 and WP 11 are detailed.



Internal cooling loop requires a return line for recompression of the non liquified part and slightly more compression power than for an external cooling loop.

The external cooling loop is selected

Cost and availability of land. Permanent or shifting locations. Water depths.

Not basecase. Offshore unloading assumes tank size of 1.5 x ship size

Cost and availability of land. Permanent or shifting locations. Water depths.

Barge for Intermediate storage for CO_2, ref. conceptual design in WP3

Lobed tanks are not considered relevant. Spherical tanks are discussed in WP3 but not selected.

Vertical tanks selected as base case

Feasible but not selected as a basecase

Feasible as a low CAPEX solution but not selected as a basecase due to HSE and additional time spent

Feasible but not selected as a basecase

The floating liquefaction facility design in WP11 is intended used in a sheltered inshore location.

Offshore location is not relevant in this work package. This also applies for the Intermediate storage.

Barge for Floating Liquefaction and Intermediate storage for CO_2, ref. conceptual design in WP11

Base case is to use the Northern Lighs facilities at Kollsnes

Choices for these items are described in WP3. The selected solutions are bunkering from ship or truck, manual system for delivery of provisions by use of truck, pallets and provision crane, conventional hose filling of potable water and shore power by manual plug in solution. The shore power is not foreseen to charge the batteries.

Figure 11 WP 3 and WP 11

2.1 Liquefaction

The CO_2 is captured from a flue gas and arrives at the liquefaction plant at 1.7 bara and 25 °C. The need of a booster pump/compression must be assessed in each individual case as the need will depend on the distance between the liquefaction plant and the intermediate storage. Before the CO_2 enters the first of three compressors, the CO_2 passes through a knockout drum (KO drum) to ensure that no liquid enters the compressor. In a three-stage compression with intercooling and condensate removal, the CO_2 is compressed from 1.7 bara to 21 bara. The CO_2 stream then passes through a dryer where the water concentration is reduced to 30 ppmv (the Northern Lights specification, ref (17)). After drying, the CO_2 is then cooled to ~-27°C with cold ammonia (-32°C), the final cooling down to transport temperature, -48.5°C is done by expanding the CO_2 from 20 bara to 7 bara.

The dryer consists of two beds containing a solid desiccant, where one is in operation while the other is regenerated. The bed is regenerated by heated dry CO_2. As mentioned above, the CO_2 is partly cooled with ammonia. The ammonia cooling loop consists of compression, condensation, and expansion. The liquefaction process is illustrated in Figure 12.

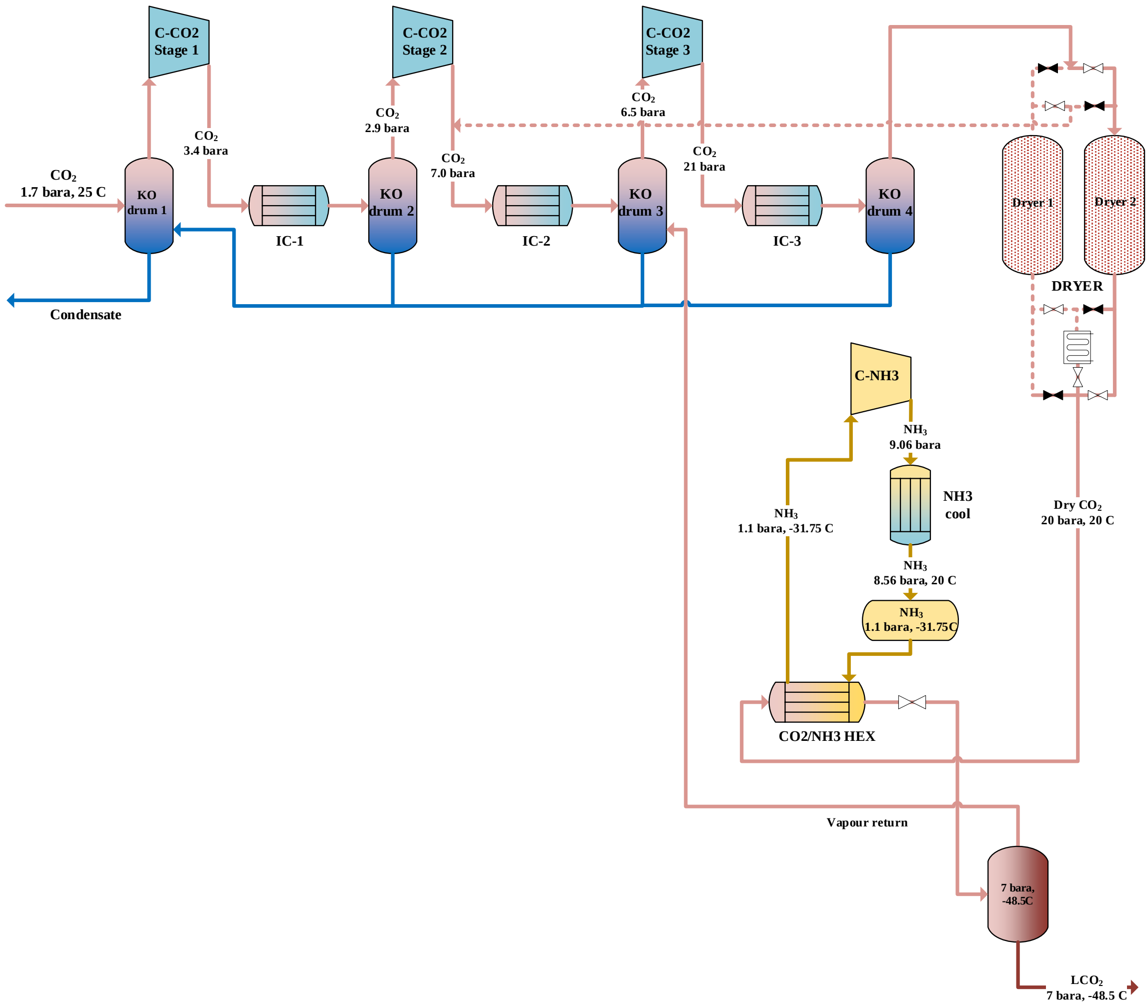


Figure 12 The liquefaction process

The arrangement of the liquefaction plant is shown in Figure 13, while the MEL is provided in Table 17. The calculated footprint of the liquefaction plant is ~525 m^2, including maintenance corridors.

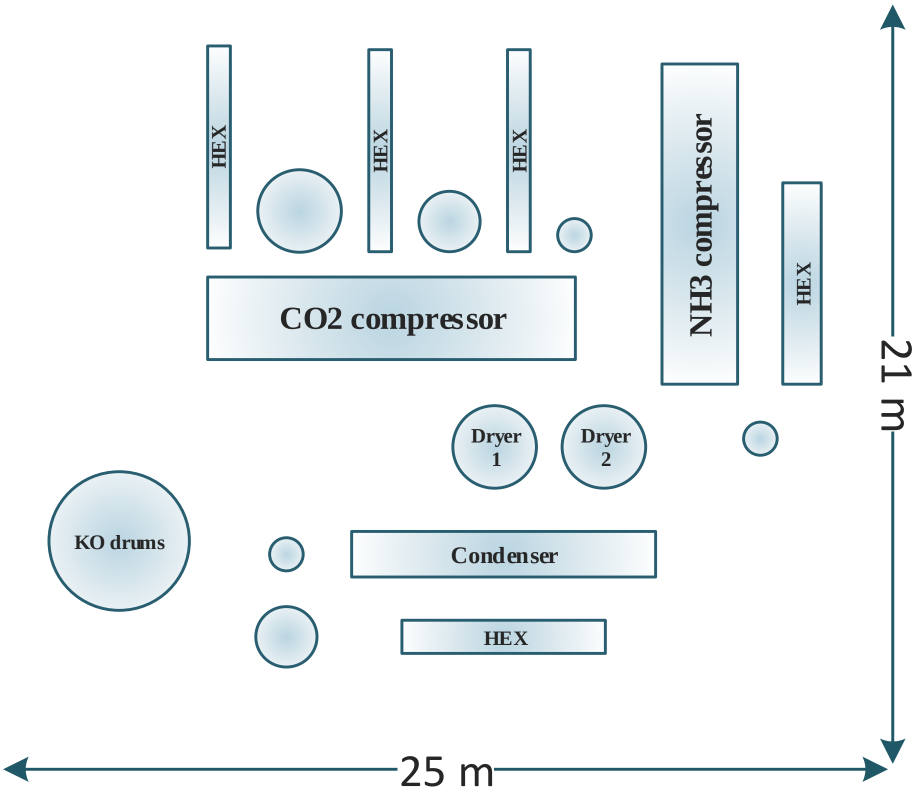


Figure 13 Liquefaction plant arrangement.

Table 17 Liquefaction MEL

Equipment	Unit	Size	Material
CO_2 compressor, COMP 1 – 3	kW	8 900	CS
NH_3 compressor, COMP	kW	16 110	CS
CO_2 – NH_3 cooler, HEX-5	m^2	707	SS316
Intercooler 1, HEX-1	m^2	603	SS316
Intercooler 2, HEX-2	m^2	506	SS316
Intercooler 3, HEX-3	m^2	488	SS316
NH_3 cooler, HEX-6	m^2	1 553	SS316
KO drum-1	m^3	52	SS316
KO drum-2	m^3	22	SS316
KO drum 3	m^3	10	SS316
Dryer 1 and 2	m^3	40	SS316

2.2 Terminal

The terminals are categorized as import and export terminals. Further, the export terminals are divided in onshore or floating terminals, with a further distinction of floating terminal with or without liquefaction and/or intermediate storage.

2.2.1 Import terminals

The base case import terminal will be at the Northern Lights projects facility at Kollsnes. The project assumes a phase 2 of the terminal with a new quay/jetty allowing for vessel lengths above 130 m and receipt of low pressure CO_2.

Figure 14 Kollsnes CO_2 import terminal, illustration from Northern Lights project *(17)*

2.2.2 Export terminals

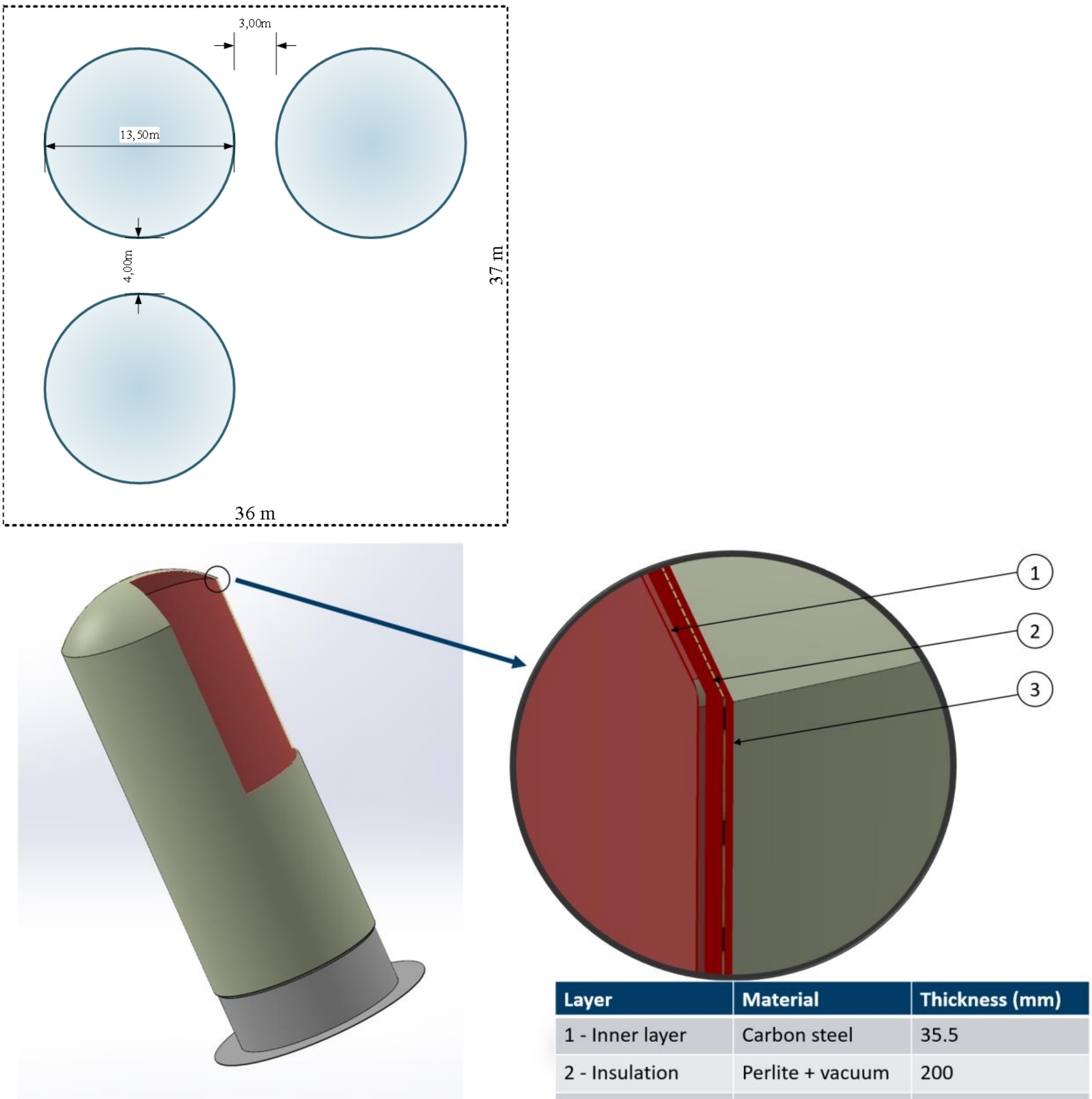
The import terminal is well described in ref (17). The potential arrangement of an export terminal, here represented by Rotterdam, is therefore the main focus. Rotterdam is today a well-established port, and it is assumed that there is no limitation on land area and quay access. However, in order to also provide a more generic assessment, the consequences of limited land area and quay access is considered as part of three different export terminal concepts:

- Concept 1 – The base case, both the liquefaction and the intermediate storage tank facility are located onshore. The ship docks at a quay or jetty during loading.
- Concept 2a – The liquefaction is onshore, the intermediate storage tank facility a floating unit.
- Concept 2b – Both the liquefaction and intermediate storage are floating, ref WP 11.
- Concept 3 – Similar to Concept 1, the liquefaction and the intermediate storage tank facility are located onshore, while the ship docks at a floating terminal (i.e. a buoy).

2.3 Intermediate storage

The largest installation on an export terminal is the intermediate storage facility, and therefore a sensitivity analysis on parameters that affect the footprint of the facility has been performed. These parameters are design storage pressure, orientation (vertical or horizontal) and capacity ratio towards ship cargo capacity (1x, 1.2x and 1.5x). The results are largely as expected with the 7 barg storage pressure, vertical arrangement and 1x cargo capacity being the least area intensive alternative with an estimated footprint of 1 330 m^2. Comparably, for a horizontal arrangement the estimated footprint is 2 365 m^2.

Vertical tanks at 7 barg design pressure is the selected base case for onshore storage, ref. Figure 15.



Layer	Material	Thickness (mm)
1 - Inner layer	Carbon steel	35.5
2 - Insulation	Perlite + vacuum	200
3 – Outer layer	Stainless steel	?

Figure 15 Onshore storage tanks, 7 barg design pressure, volume is 1x ship's cargo capacity

2.3.1 Floating storage

An alternative to onshore intermediate storage is to arrange for intermediate storage on a stationary barge. A simple barge design is shown in Figure 16. On a floating unit, horizontal tanks are the preferred solution. The tanks are the ship tanks developed in WP 6.

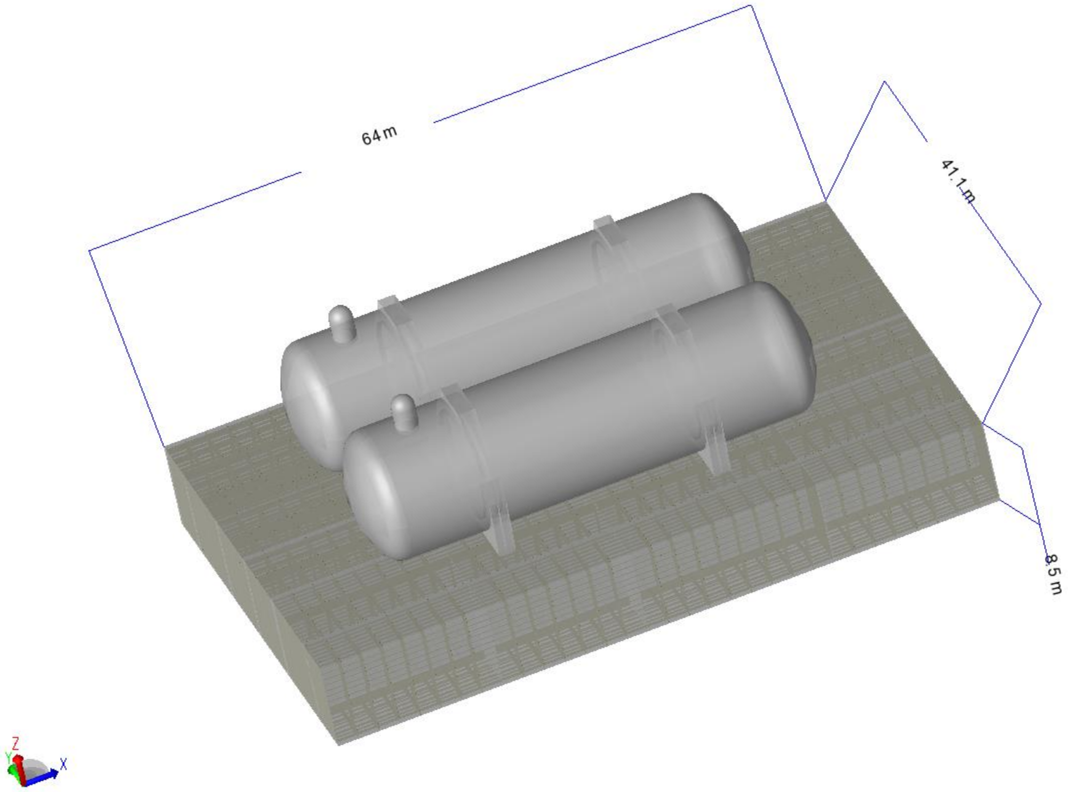


Figure 16 Barge arrangement.

Size and weight data for the barge:

- Steel weight of barge without tanks: Appx. 2 930 t
- Total steel weight of empty tanks with supports: Appx. 1 350 t
- Weight of tank content: Appx. 12 000 t
- Weight of extras: Appx. 1000 t
- Total weight: 17 280 t
- Design draught (fully loaded): 6.4 m

Table 18 Intermediate storage tanks on floating unit, 7 barg design pressure, volume is 1x ship's cargo capacity

Equipment	Unit	Size	Material	OD, m	Length, m
Storage tanks, 2 horizontal tanks	m^3	5 219*2	VL 4-4L	12.55	44.2
Export pump, 2 units	t/h	600*2	SS	-	-

2.4 Port facilities/ship interface

Based on a port technology study and selection, the interfaces between the ship and the port facility has been defined. Typical choices made in the WP 3 report, ref (4) are between automated high CAPEX solutions such as loading arms and mooring vacuum pads versus manual high OPEX solutions such as flexible loading hoses and conventional mooring. The interfaces specified in the report are presented in Table 19 As it can be seen from the table the requirements are slightly different for the offloading (Kollsnes) and the loading ports (Rotterdam).

Table 19 Interface port facility to ship

Interface item	Ship Interface point Rotterdam	Port facility Interface point Rotterdam	Rotterdam connections, flowrates etc	Ship Interface point Kollsnes	Port facility Interface point Kollsnes	Kollsnes connections, flowrates etc
Mooring of ship	Ship side	Vacuum pads on quay	20 t holding power per vacuum pad	Ship mooring lines	Quay bollards	Mooring minimum breaking load appx 350 kN
Loading and unloading liquid CO_2	End flange on the branch off from the ship cargo header	End of Loading arm for Cargo	DN 400 flange, flowrate 1200 t/h at 8.2 barg and -50°C	Flange on a branch off from the ship cargo header	End of Loading arm	DN 400 flange, flowrate 1200 t/h at 8.2 barg and –50°C
Gas return from tank when loading and unloading	End flange on the branch off from the ship gas return header	End of Loading arm for Gas return	DN 250 flange	Flange on a branch off from the ship gas return header	End of Loading arm for Gas return	DN 250 flange
Electrical power to ship	Socket on ship	End of power cable from quay	Delivery of 500 kW at 690V/50 Hz	Socket on ship	End of power cable from quay	Delivery of 800 kW at 690V/50 Hz
Potable water to ship	Not applicable	Not applicable	Not applicable	Onboard connection for hose	End of hose from quay	Delivery of 23 m^3 through a DN 100 hose/flange connection
Bunkering of fuel	Flange for fuel loading	Not applicable	TBD	Not applicable	Not applicable	Not applicable
Provisions for crew	Crane hook from ship provision crane	Pallet with provisions on the quay within reach of the crane	Provision Crane SWL 1t	Not applicable	Not applicable	Not applicable

3 WP 11 FLOATING LIQUEFACTION FACILITY

3.1 Floating storage and liquefaction concept

A design/concept is developed for a floating liquefaction and storage unit for CO_2. This concept is briefly mentioned as Concept 2b in WP3, and further developed in WP 11, ref (5). There are several advantages with having a floating installation. In addition to the reduced use of land area and cost, the possibility of moving the installation to a new location when the need for it at one location ceases, is attractive.

The storage tanks, two horizontally lengthwise arranged with a total volume matching the base case ship, are placed in the hull, with the CO_2 liquefaction topside. For a floating terminal for intermediate storage, there should be no issues with space availability for the liquefaction plant due to the larger footprint needed for the storage tanks. The liquefaction plant operates continuously on gaseous CO_2 coming from the capture plant located onshore, therefore continuous fluid transfer is needed. In addition, the compressors and pumps are electrically driven, and shore power supply is needed.

In WP3 the purpose of the floating installation was solely intermediate storage of the CO_2 awaiting the cargo ships arrival and therefore not specifically designed for flexibility. Here, a more complex installation is designed, with liquefaction of CO_2 and intermediate storage, and with focus on flexibility. The storage tanks are arranged horizontally lengthwise in the hull with a total volume matching the ship Concept B in WP 2, ref Figure 35. The footprint of the liquefaction plant is smaller than the footprint of the storage tanks, meaning that the size of the storage tanks to a large degree dictates the size of the terminal.

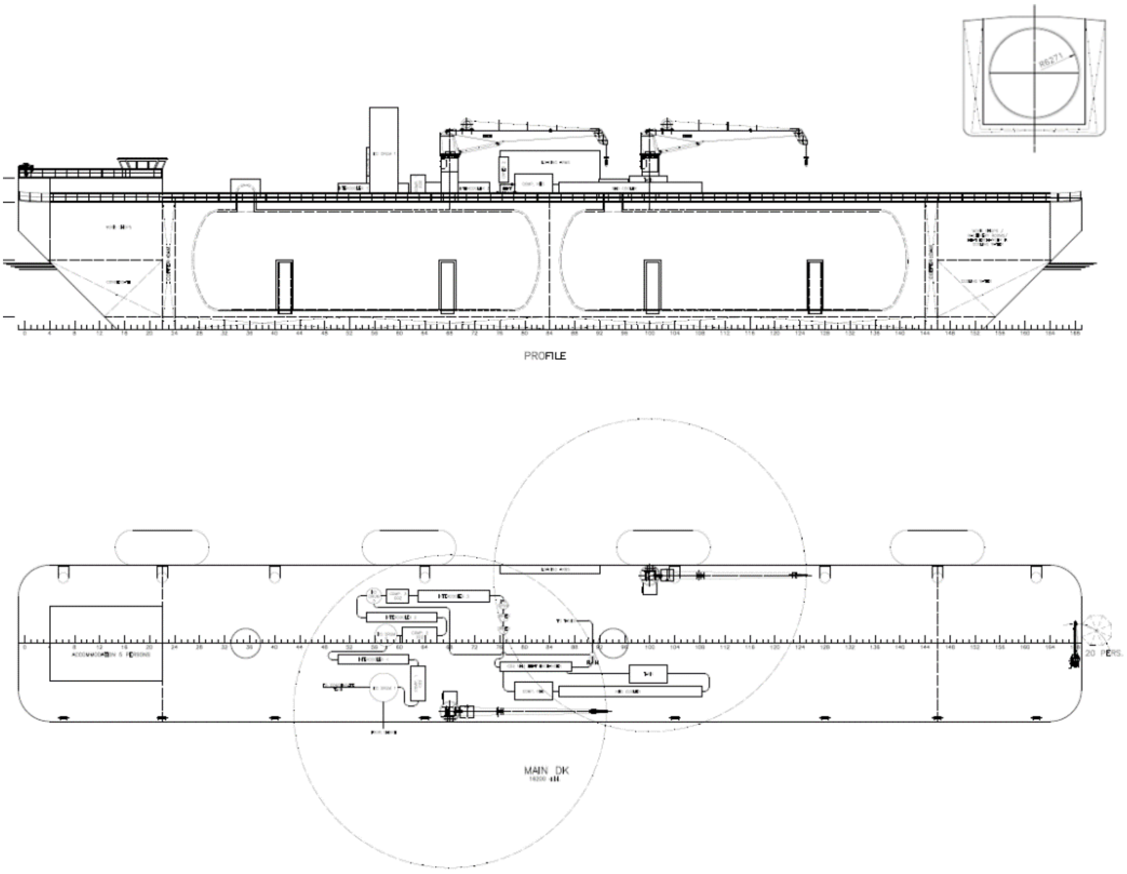


Figure 17 General arrangement of the floating terminal

Table 20 Floating CO_2 liquefaction and storage terminal

Parameter	Value	Unit
Length overall	~136	m
Breadth	20.0	m
Depth to main Deck	16.2	m
Design draught	8.0	m
Liquefaction capacity	241	tCO_2/h
Storage capacity	10 000	m^3
Unloading rate	600	tCO_2/h per tank
Design temperature	-55	°C
Design pressure	7	Barg
Systems on board	Freshwater cooling system for cooling of inter coolers 1, 2 & 3	
	Air compressor for service air and instrument air	
	Air dryers for instrument air	
	Seawater cooling system. (Flow to be set to stay within allowable temperature increase at the site)	
Utilities from shore	Fresh water make-up water for freshwater cooling system	
	Electric power supply for the liquefaction unit and systems on board the barge	
	Connection for CO_2 for liquefaction	
Maritime equipment	Quayside mooring with standard bollards, seaside mooring with quick release bollards. Yokohama fenders to be placed on seaside of barge.	
	Crane coverage of liquefaction plant equipment, for removal to shore, and to assist moored gas vessels.	
	Firefighting and rescue & escape equipment according to IMO rules.	
	Living quarters for crew.	

3.1.1 Special considerations

The unit shall be located in a protected environment such as port, bay, fjord, estuary, etc. The assumption is that there will not be weather conditions severe enough to require unmooring of the barge, and that side by side loading may be considered to have the same regularity as for a quay/jetty.

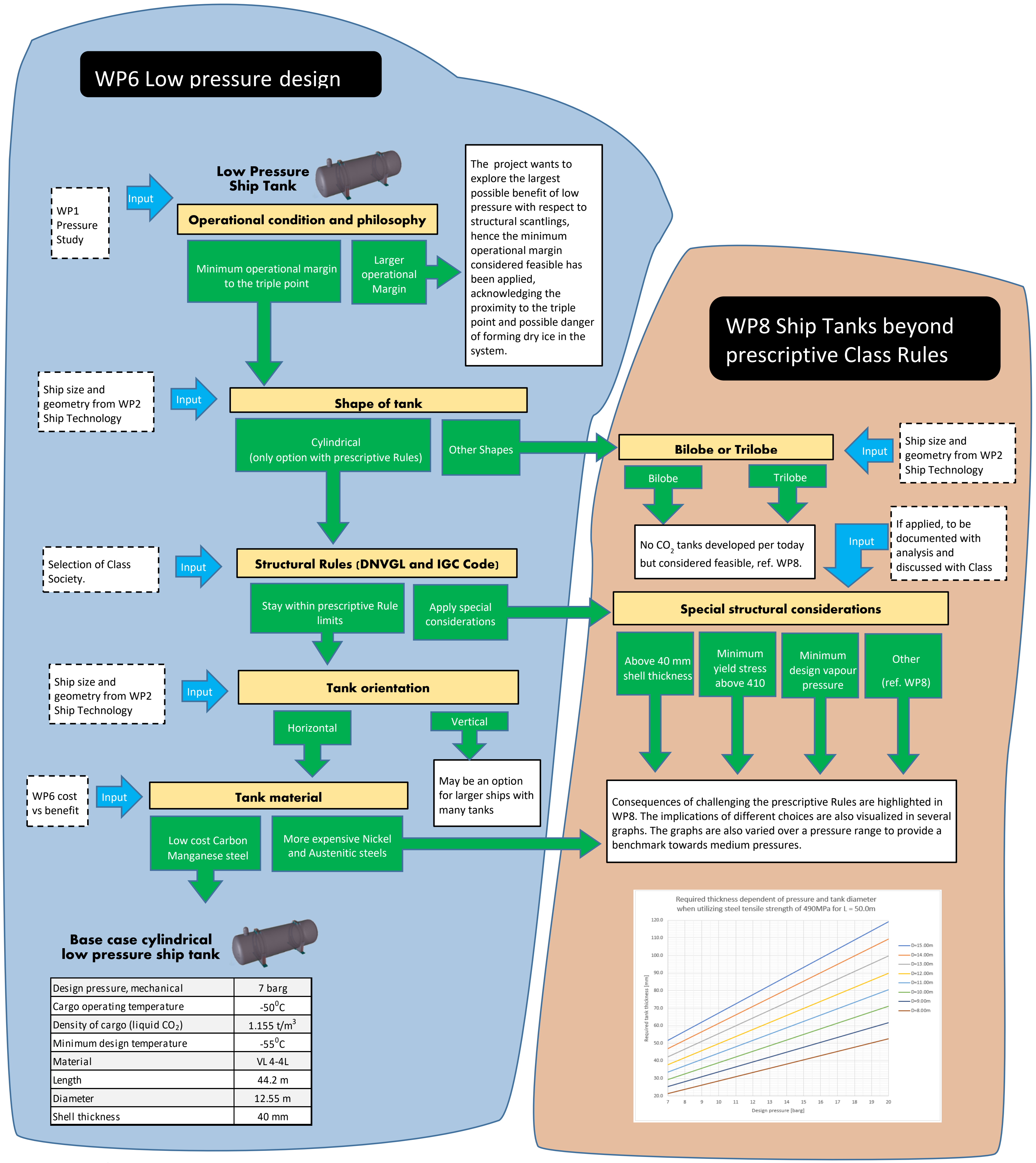
The barge is assumed to be an extension of the onshore terminal and that it is subjected to the laws and regulations that govern the onshore operations. If any special considerations in regard to laws and regulations are needed, this needs to be assessed from location to location.

The terminal could be moored at a quay/jetty or detached from land. The floating terminal is designed for operating in protected waters (inshore) with arriving vessels berthing alongside the terminal. Therefore, if the solution with a terminal detached from land is selected, it should be with spread mooring keeping the terminal in a fixed position.

4 WP 6 LOW PRESSURE DESIGN

Following the selection of the low pressure condition as the basis for the containment systems in the project, a low-pressure tank suitable for ship transport of liquefied CO_2 has been developed. The target has been to challenge the established medium pressure transport, by providing larger and more cost-efficient cargo tanks. The tank design is the main output of WP 6. A key issue has been to find the minimum operating pressure still providing a sufficient operating window and sufficient margin to the triple point where the CO_2 turns solid.

The tanks structural design has been based on the DNVGL Rules and the IGC Code applicable for design with cylindrical tanks of Type C. Staying strictly within the text of the prescriptive Rules/Code limits the shell thickness to 40 mm in addition to other limitations such as cylindrical shape, minimum yield limit below 410 MPa etc. These limitations applied in WP 6 are quite conservative compared to existing and future ship projects and may be dispensed from by special considerations from the Class, provided documented by analysis and tests as a safe design. In WP 8 the possible benefits of challenging the prescriptive rules has been explored. Also use of higher cost materials is evaluated. Reference is made to Figure 18 for a schematic description of WP 6 and WP 8.



The project wants to explore the largest possible benefit of low pressure with respect to structural scantlings, hence the minimum operational margin considered feasible has been applied, acknowledging the proximity to the triple point and possible danger of forming dry ice in the system.

May be an option for larger ships with many tanks

No CO_2 tanks developed per today but considered feasible, ref. WP8.

If applied, to be documented with analysis and discussed with Class

Consequences of challenging the prescriptive Rules are highlighted in WP8. The implications of different choices are also visualized in several graphs. The graphs are also varied over a pressure range to provide a benchmark towards medium pressures.

Design pressure, mechanical	7 barg
Cargo operating temperature	-50^{0}C
Density of cargo (liquid CO_2)	1.155 t/m^3
Minimum design temperature	-55^{0}C
Material	VL 4-4L
Length	44.2 m
Diameter	12.55 m
Shell thickness	40 mm

Figure 18 WP 6 and WP 8

4.1 Pressure operating window

The small margin between the mechanical design pressure at 7 barg and the triple point at 4.18 barg leave little operating freedom. The absolute minimum operating pressure, where cargo pumps and manifolds shall shut down is according to RuShip Pt 5 Ch 7 Sc 17 11.1, ref (18), at 0.5 bar above the triple point, in this case 4.7 barg.

Regarding the maximum pressure, this depends on the characteristics of the pressure safety valve.
The span where the PSV starts to open to where it is fully open is denoted as simmer and this is typically at 98% of the set pressure of pressure safety valve. In this case this is 6.8 barg.
After the PSV is opened is stays open until typically 92.5% of the set pressure, in this case this is 6.4 barg.
By using a pilot operated valve, the blow down range may be reduced.
These numbers are shown in Figure 19.

Looking at these numbers the operating window with regard to pressure would range from 4.7 barg up to 6.4 barg. By using a pilot operated pressure safety valve this window could be extended up to 6.8 barg.
If a pilot operated PSV is chosen it must be safeguarded that the pilot piping will not be clogged by dry ice.

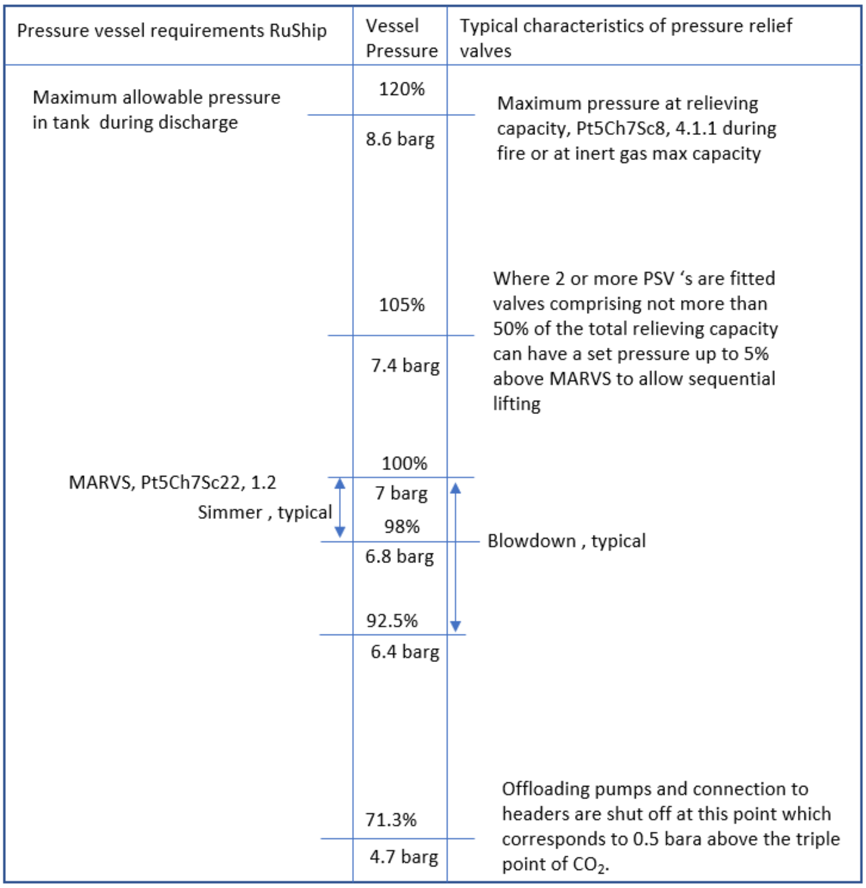


Figure 19 Pressure safety valve requirements and characteristics based on API 520, ref (19) and RU Ship Pt5Ch7, ref (18)

4.2 Structural analysis

A horizontal low-pressure cylindrical CO_2 cargo tank including support structure has been developed and documented to AIP-level. The tank is optimized with respect to ratio between cargo volume to tank steel weight keeping maximum vessel shell thickness at 40 mm. The design is based on the parameter values listed in Table 21.

Table 21 Characteristic data for base case CO_2-tank

Parameter	Symbol	Value	Unit
Design pressure, mechanical	P_0	7	barg
Cargo operating temperature	T_{cargo}	-50	^0C
Density of cargo (liquid CO_2)	ρ_c	1.155	t/m^3
External design pressure	Ped_{design}	0.45	bar
Maximum design temperature		+60	^0C
Minimum design temperature		-55	^0C
Design life of CO_2-tank, ref. (18) Sec.4 Paragraph 2.1.1		25	years
Material of cargo tank	VL 4-4L	-	-

The total weight of the tank with its support is approximately 667 tonnes with a cargo volume of 5 194 m^3, length of 44.2 m and diameter of 12.55 m. The volume/steel weight-ratio is calculated to 7.784 m^3/tonnes. The tank is not designed for full vacuum and therefore a vacuum valve will need to be installed to protect the tank against under pressure. The maximum external pressure is 0.45 bar.

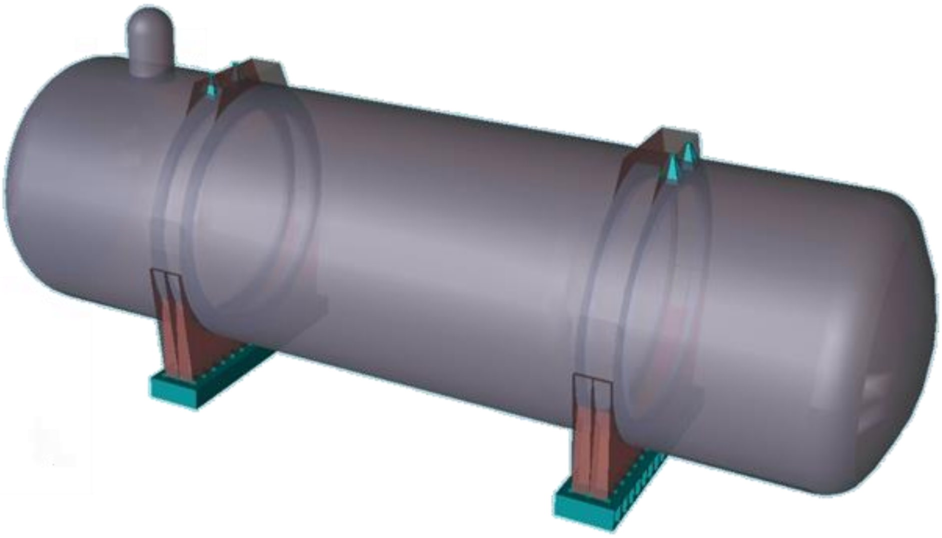


Figure 20 Tank structural model

The tank is designed with a 2.2 m diameter dome where cargo pumps and PSVs will be installed and two upper and lower supports, where one is fixed and the other longitudinally sliding allowing for thermal expansion. Four ring stiffeners, two and two are positioned at each of the lower support end-plates.

The material study concluded a carbon manganese steel to be the best choice for the tank, for our case the selected carbon-manganese steel quality is DNVGL quality code VL 4-4L.

A selection of steels is listed in Table 22 with respect to applicability for the minimum design temperature of -55˚C and minimum design vapour pressure equal or less than 7 barg, all based on tank length 44.2 m. This does not imply that the tank cannot be operated at lower pressure. The requirement about minimum design vapour pressure is intended to ensure that dynamic stresses are sufficiently low and has its basis in fracture mechanics and crack growth. Hence there is a direct relationship between maximum tensile strength and minimum design vapour pressure. For the tank length of 44.2 m, we can see from Table 22 that maximum material tensile strength to be utilized is between 540 and 570 MPa or more exactly 546 MPa. If the tank length is reduced to, as an example, 35 m the maximum tensile strength that can be utilized is 613 MPa.

Table 22: Pressure vessel steels qualities applicable for minimum design temperature equal -55^{0}C and for tank length 44.2 m

Grade DNVGL, BS ASTM or EN10028-3	Yield/Tensile 40 mm [MPa]	Maximum tank diameter t=40 mm [m]	Maximum tank diameter t=50 mm [m]	Tank volume t=40 mm [m^3]	Tank volume t=50 mm [m^3]	Relative cost of steel quality %
P355NL1	345/490	N/A temp.	N/A temp.			0%
P355NL2	345/490	N/A temp.	N/A temp.			0%
BS 1501 225 490B	345/490	N/A temp.	N/A temp.			0%
ASTM A203 F	380/485	N/A temp.	N/A temp.			0%
VL 2-4L	255/400	10.85	13.17	3913	5704	0%
VL 4-4L	325/490	12.55	15.18	5194	7513	0%
VL 0.5Ni/a	275/420	11.24	13.62	4189	6094	+8%
VL 0.5Ni/b	345/490	12.55	15.18	5194	7513	+8%
VL 1.5Ni/a	265/470	12.19	14.74	4905	7100	+24%
VL 2.25Ni	295/500	12.74	15.39	5351	7723	+36%
VL 3.5Ni	345/540	13.47	16.25	5963	8574	+56%
VL 5Ni	380/570	N/A ***	N/A***			+81%
VL 9Ni	480/640	N/A ***	N/A ***			+146%
VL Mn 400	400/800	N/A ***	N/A ***			+85%

* Tank diameter calculations except for VL4-4L is based on preliminary calculations and is to be considered as a guidance.
** Steel cost is approximate and is to be considered as a guidance.
***Not applicable due to design vapour pressure too high

The prices and the complexity of the production process increases as we go down the list in Table 22. The first applicable steel in the list is VL 2-4L but this has the lowest yield and tensile strength. The next and last simple carbon manganese steel with quality code according to DNVGL ref. (20) and Table 22, is VL 4-4L with max 0.16% carbon and from 0.70 to 1.60% manganese. The minimum yield stress for this steel for thicknesses from 35 to 40 mm is 325 MPa and minimum tensile strength is 490 MPa. This steel quality VL 4-4L, is then selected for the CO$_2$ tank to be designed and FE-analysed according to design basis.

Findings from the design process:

- For an applicable tank steel quality, the material tensile strength is directly connected to minimum design vapour pressure trough rule formulas. Higher strength material will increase minimum design vapour pressure. With selected steel quality VL 4-4L minimum design vapour pressure becomes 5.03 barg. Only small increase in material strength will imply no operation margin to the mechanical design pressure of 7 barg. Hence increasing material strength is not an option unless for present Ltank/D0, the important tank-parameter “length” is reduced. Note that this does not imply that the tank cannot be operated at a pressure below the minimum design vapour pressure.
- Both tank diameter 12.55 m and length 44.2 m are on the limit within the selected base case.
- Reference is made to Table 22, where it is shown that by increasing the material thickness from 40 mm to 50 mm the tank diameter can be increased to D=15.18 m and the volume becomes 7513 m^3. This modification requires special consideration by the class authorities.
- Elliptical dome cutout in cylinder shell is necessary to reduce stress concentration for the dominant stress direction in transverse direction of the tank cylinder. Aspect ratio 0.6 is selected.
- Support design is critical with regard to stress raisers or hot spots in the tank vessel shell.
- Support horizontally on top of tank is necessary.
- Swash bulkheads can give significant bending stress raise in the tank shell when they restrain tank membrane expansion under pressure. However, the Rule assessment concludes that swash bulkheads are not necessary.
- Building lower supports too high and stiff will introduce local high stresses in the tank shell. The tank need freedom to expand.
- 4 ring stiffeners are needed to stiffen the tank in a distributed way.
- Piping to and from the tank need to consider deflections of the tank itself and be designed with freedom for this.

4.3 Other work within WP 6

In addition to the results presented above, the work within WP 6, ref (6) comprises:

- The loading and unloading process
- Process simulation in Unisim R460.2
- Design and sizing of the necessary equipment needed to complete a cargo system around the tank design
- Development of a safe design by performing a HAZID
- Definition of a road map for further technology qualification
- Tank principal drawings with scantlings
- Master Equipment List
- P&ID of cargo system with two tanks
- Refrigeration for liquefaction

5 WP 8 SHIP TANKS BEYOND PRESCRIPTIVE CLASS RULES

Consequences of challenging the prescriptive Rules are highlighted in WP 8, ref (7). The implications of different choices are also visualized in several graphs. The graphs are varied over a pressure range to provide a benchmark towards medium pressures.

5.1 Cylindrical tanks

Ship rules applicable for transportation of liquefied CO_2 ref. (18), have multiple statements that restricts the utilization of high tensile steel and steel scantlings in so called type-C tanks for liquefied gas tankers. Some of the restrictions can be challenged in cooperation with ship class society. The relevant restrictions are:

- 40 mm maximum thickness without special considerations (challengeable)
- Minimum yield stress not to exceed value of 410 MPa (challengeable)
- Hardness of welded and heat affected zones (challengeable)
- Mechanical stress relieving as alternative to post weld heat treatment (conditional)
- Yield to tensile ratio (cond./chall.)
- Requirement for material ductility (challengeable)
- Minimum design vapour pressure to ensure crack safety (challengeable)

The 40 mm thickness limit has not been challenged during the tank design in WP 6, but for other projects several type-C tanks with larger thickness than 40 mm have been approved in cooperation with class. Figure 21 illustrates the required tank membrane thickness dependent of pressure and tank diameter for L = 50 m and material VL 4-4L. The benefit of going from 40 mm to 50 mm thickness at a design pressure of 7 barg is more than 2 m added to the diameter of the tank.

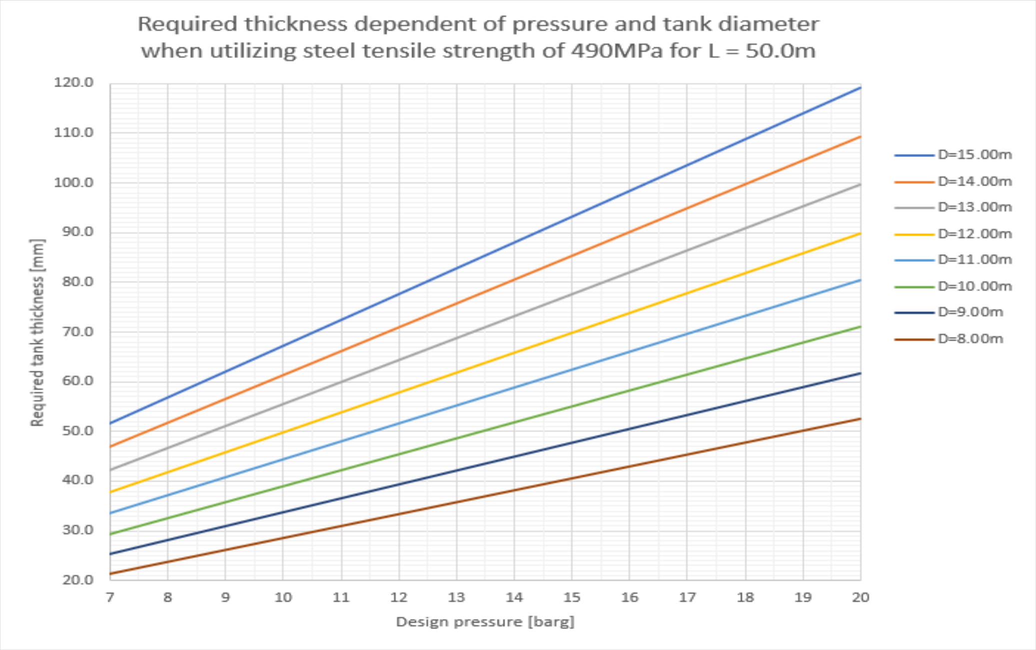


Figure 21 Required tank membrane thickness dependent of pressure and tank diameter for L = 50 m and material VL 4-4L

The conclusions are:

- 800 MPa tensile strength is considered upper limit for steel materials applicable for tank design. This material strength is fully utilizable for design pressures above 10 to 15 barg dependent on tank dimensions.
- For nickel and carbon manganese steels, yield strength equal half of tensile strength is the rule optimum combination of material ductility and strength.
- Tensile strength needs to be restricted further below 800 MPa for low design pressures in combination with large tanks. Tanks can then be designed using lower tensile strength materials such as applied in WP 6.

5.2 Bilobe and trilobe tanks

Several geometrical variants of the independent type C cargo tank exist. These variants are designed by combining two, three or more cylinders. They are designated bilobe, trilobe and multilobe. The cylindrical forms intersect and are joined by welding. The outer shell of the tank is seam welded along the longitudinal intersection lines. The motivation for using such lobed tanks is to increase the utilization of the hull volume. With equal diameter on the basic cylindrical shape the bilobe and trilobe tank will offer increased volume as illustrated in Figure 22.

The lobed design is described as a common arrangement for semi-pressurized gas carriers, ref (21). The design may include a taper if placed in the front end of the ship.

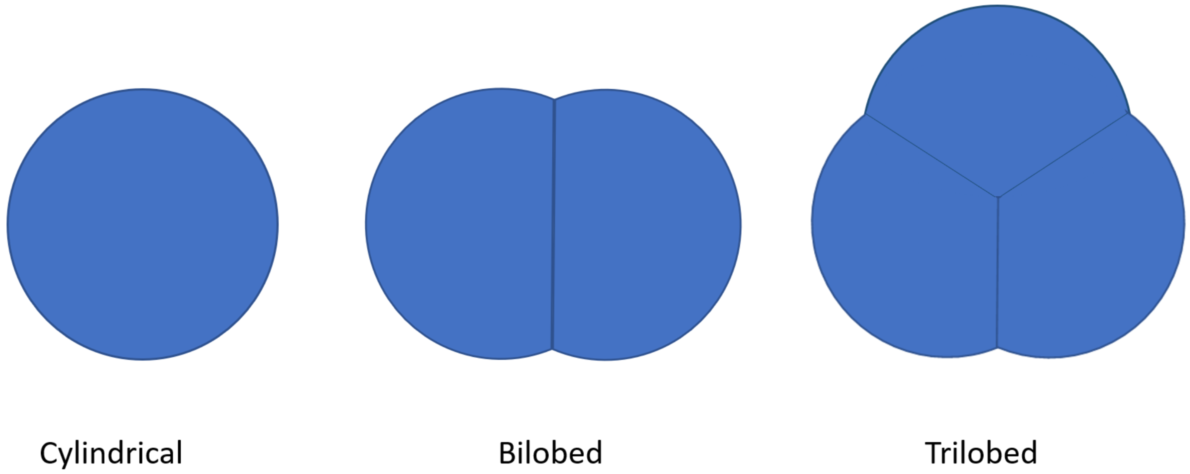


Figure 22: Front view of 3 variants of the independent type C cargo tank. Cylindrical, bilobed and trilobed. The illustration shows the relative increase in volume if the basic cylindrical diameter and tank length is equal.

The state of the art regarding independent cargo tank C of bilobe and trilobe design have been investigated, by the means of a literature search.

There are several examples of gas carriers with bilobe and trilobe tanks with volume between 7 500 m^3 up to 23 000 m^3 for LPG, LNG and LEG transportation (p=3.5 to 4.5 barg, in combination with t= -100°C to -160°C). There are also examples of smaller fully pressurized bilobe tanks 3 250 m^3 (p=18.6 barg, t = - 10°C).

None of the bilobe or trilobe cargo tanks are suitable for liquid CO_2 without further improvements with respect to cargo density, pressure and temperature, and adaption of size.

6 WP 13 BENCHMARKING NORTHERN LIGHTS

The CO2LOS II project base case, ref Figure 24 and the Northern Lights project, ref Figure 25, share many of the same solutions, there are however important differences. A benchmarking between the projects is the scope of this report. The Northern Lights project overlaps the CO2LOS II project on the ship transport and the import terminal quay facilities with intermediate storage, reference is made to Figure 23.

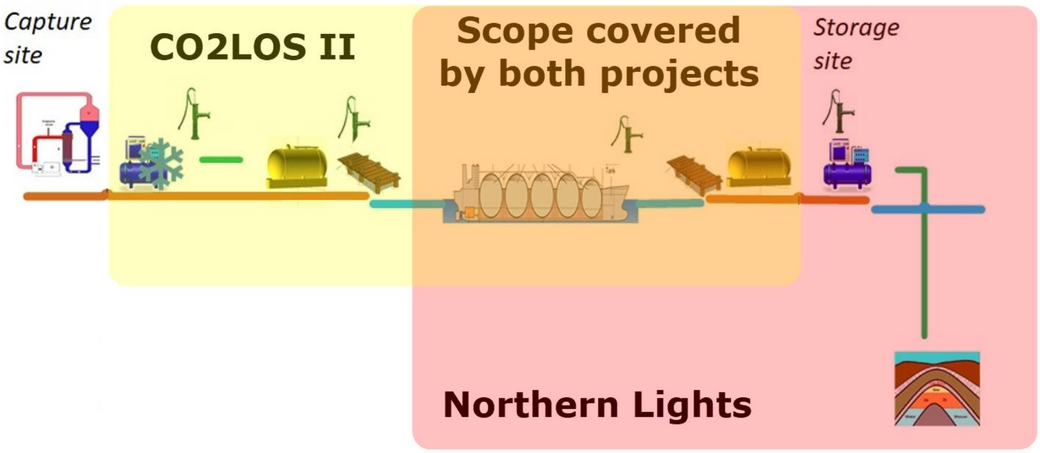


Figure 23 Common scope in Northern Lights and CO2LOS II

Both projects are however dependent on the boundary conditions from the other parts of the CCS chain. Comparison is done on all elements found relevant from capture to storage. When comparing with the CO2LOS II project it is referred to the base case North Sea trade from Rotterdam to Kollsnes.

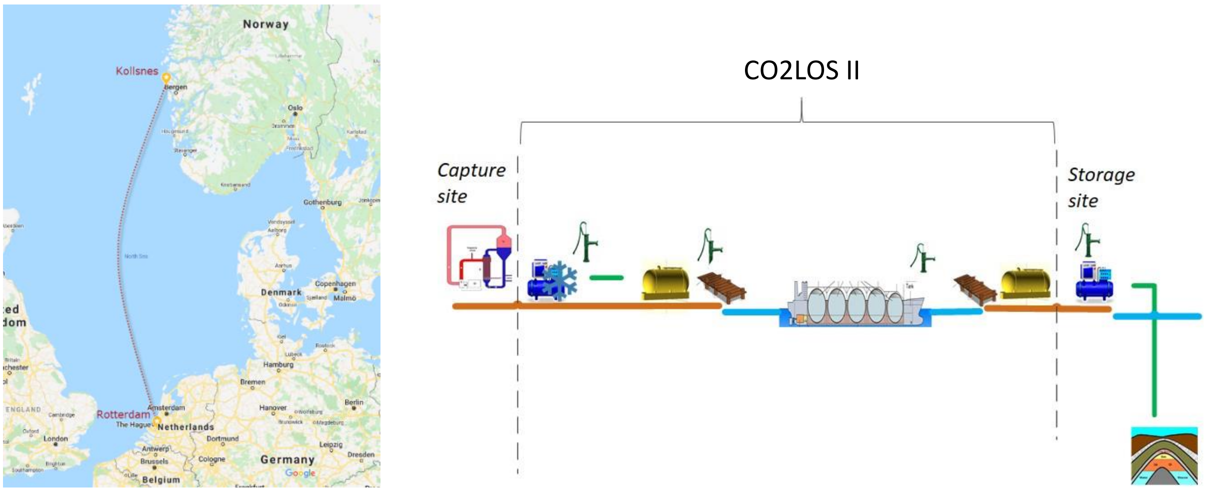


Figure 24 CO2LOS II project base case, ref (8)

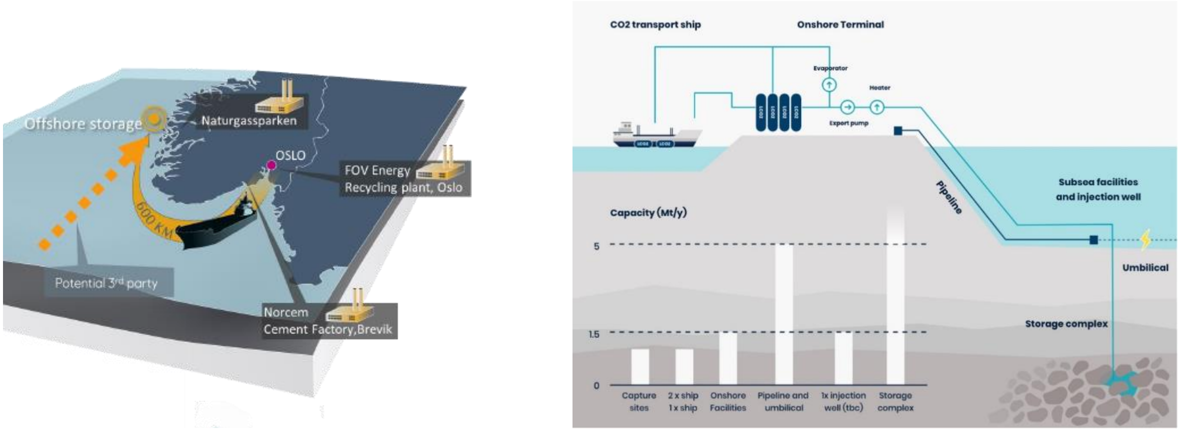


Figure 25 Northern Lights Project, ref (22)

6.1 Capture location and volume

The initial volumes of only 0.4 Mt/y from each capture location and the rather short sailing distance of 300 nautical miles in the Northern Lights project, compared to the 2.0 Mt/y and 540 nautical miles in the CO2LOS II project, affects the capacity needs in the logistics chain. The CO2LOS II project evaluates logistic profiles for a wider range of ship sizes and number of ships than what is initially considered relevant for Northern Lights. With delivery of 3rd party volumes from continental Europe and a development of a phase 2 at the reception facility at Kollsnes, the Northern Lights project is expected expanded with larger/more ships.

6.2 Liquefaction

Assumably the most important single difference between the two projects is the choice of transport pressure for the liquefied CO_2.

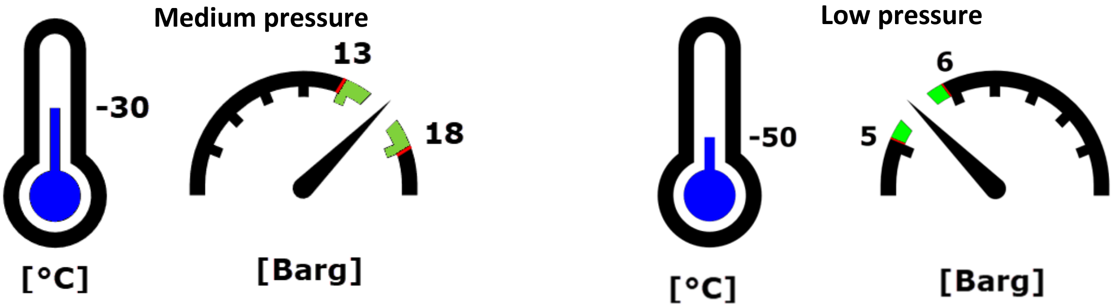


Figure 26 CO_2 transport condition (medium and low pressure)

The Northern Lights project selected to comply with the current industry standard for ship transport of rather small volumes (up to 1800 m^3) of CO_2 intended for the food and beverage industry. This pressure is normally referred to as medium pressure in the context of ship transport of liquefied CO_2. Typically, when operating at medium pressure this means a pressure between 13-18 barg with a corresponding operating temperature of around -30°C. The following advantages are seen with this approach:

- It is a mature technology with a high TRL. The solution can be implemented today without further technological development.
- Operations will be done with a comfortable margin to the point where the liquid turns to solid (dry ice) which happens around 4.2 barg.
- The total cost of liquefaction will be less than for lower pressures as it is more costly to lower the temperature than it is to increase the pressure.
- Tank material requirements related to temperature are less stringent.
- Higher yield strength materials can be utilized when designing according to the relevant IGC Code, ref (23).

The CO2LOS II project applies a low pressure strategy for design of tanks and corresponding systems. Low pressure in this context is below 10 barg. With a target operating pressure of only 5-6 barg in the CO2LOS II project, the margin to the triple point is pushed to a minimum in order to explore the full benefits and challenges with the low pressure alternative. Typical findings are:

- Increased density of liquid compared to medium pressure, allows for transport of more CO_2 per volume.
- Larger tank designs are possible as the stress level in the structures decreases with the reduced pressure.
- Compared to similar size of tanks with a medium pressure design, the low pressure tanks can be made with thinner plates, less material cost and reduced weight due to the reduced stresses.
- In order to maintain the pressure and temperature of the tank when emptied, a vapor phase of CO_2 must be left in the tank. When operating at low pressure this vapor phase CO_2 which cannot be unloaded is around 1.8% of the cargo at 6 barg and 4.0% at 15 barg. Hence less of the CO_2 needs to be carried back with the ship when operating at low pressure.
- The possibility of designing larger tanks with less weight provides better flexibility to fit the tanks with the ship geometry.

In a relevant study, ref (24), it is shown that 7 bar ship transport is more economical than 15 bar for most distances and volumes even with the increased cost of liquefaction for low pressure included in the transport cost. However, when being “the first of a kind” project with a short timeline to realization such as Northern Lights, it makes sense to reduce the technological development and associated risk where possible. This is assumed to be the background for the selection of medium pressure. Still, the project has put quite an effort into maximizing the ship cargo tank size by pushing the limits of the current structural rules. This also involves a potential risk and may be a cost driver during production of the tanks. Also, it is a risk that the project sets an uneconomical industry standard for the pressure.

The application of low pressure is easily found to be the sensible choice for conceptual work as performed in CO2LOS II. It may be argued that the TRL is not sufficient without a further technological development of the low pressure concept, however rules and regulations are all in place, it is more a matter of finding the minimum pressure allowing for a sufficient operational margin to the point of CO_2 solidification. It is foreseen that this will be an operating pressure of around 6-9 barg in the future.

6.3 Intermediate Storage, export site

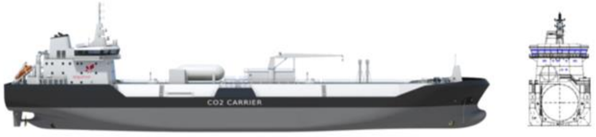
The effect of the selection of medium vs low pressure is not only relevant for the ship tanks but also affects the design of the intermediate storage tanks. Construction of such tanks will be cheaper and contain more CO_2 per volume by applying low pressure, as argued in the previous chapter.

6.4 Export terminal facilities

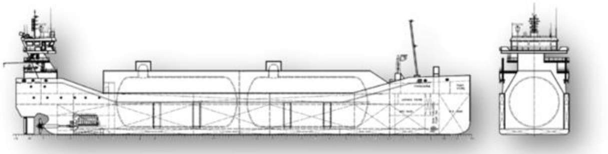
The CO2LOS II project has selected automated mooring systems and CO_2 loading arms to increase efficiency and improve HSE during operations. This increases the CAPEX investments on the terminal. The absolute CAPEX cost would be more or less equal if installed on the terminals to be used in Northern Lights. The CAPEX cost per volume of transported CO_2 would however be 5 times as high for the Northern Lights project. Hence such an investment may be too costly for Northern Lights but still reasonable for the CO2LOS II project.

6.5 Ship transport

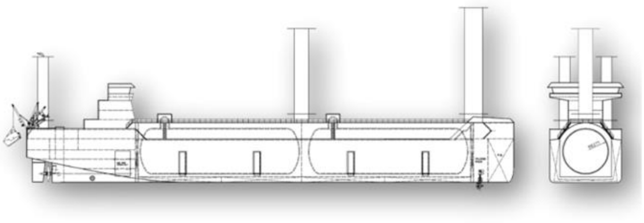
CO2LOS II has developed a low CAPEX conversion Concept A for short depreciation periods (5-10 years) and a low OPEX newbuild Concept B for longer depreciation period (20-25 years). The following comparison with Northern Lights is done separately for each of the two CO2LOS II concepts. The medium pressure vs low pressure pros and cons is already highlighted in chapter 6.2, also for ship transport and is not further discussed but listed as a relevant point.



The Northern Lights ship concept



Concept A – Ship Conversion based on donor bulk carrier



Concept B – Future Technology Ready Concept

Figure 27 Ship Concepts Northern Lights and CO2LOS II

6.5.1 Northern Lights vs CO2LOS II Concept A

The main differences between the Northern Lights ship concept and the CO2LOS II Concept A are:

- Northern Lights apply medium pressure, CO2LOS II low pressure, ref chapter 6.2.
- Concept A apply slow steaming (10 knots vs Northern Lights concept 14 knots) to reduce GHG emissions and OPEX cost on fuel. The penalty is less utilization of the ship, with associated costs.
- The Northern Lights engine run on LNG reducing CO_2 and NOx emissions and eliminating SOx emissions. However, LNG as fuel introduces methane slip which is contributing to the GHG emissions. Concept A intends to use the original engine of the converted vessel and to run on VLSFO in order to comply with mandatory emissions limits within the intended operational area. The cost of VLSFO is higher than normal MDO and HFO.
- Ship type 2PG allowing for transport also of LPG is the basis of design for the Northern Lights concept. CO2LOS II uses the less stringent ship type 3G as a basis of design. Advantage by applying 2PG can be option for return cargo and increased flexibility with respect to alternative use of the ship.

6.5.2 Northern Lights vs CO2LOS II Concept B

The main differences between the Northern Lights ship concept and the CO2LOS II Concept B are:

- Northern Lights apply medium pressure, CO2LOS II low pressure, ref chapter chapter 6.2.
- Concept B also apply slow steaming, ref Concept A.
- In addition, in the CO2LOS II vessel, wind assisted propulsion and resistance reducing devices is installed to further lower the GHG emissions.
- Due to the slow speed, wind assisted propulsion and energy saving devices, the required engine power is much less for Concept B than for Northern Lights. LNG engines of the small size needed for Concept B are not commercially available today, hence Concept B shall be equipped with a diesel engine capable of running on VLSFO, bio diesel and convertible to ammonia, methane, and ethane.
- Ship type 2PG vs 3G, ref Concept A.

6.5.3 General

In light of the Norwegian Shipowners Association’s objective, to only order vessels with zero emission technology from 2030, ref (25), the ship concept of the Northern Lights project may not seem very ambitious. Still, acknowledging that the main target of Northern Lights is the implementation of the CCS transport chain as soon as possible, it is reasonable to select well known and low CAPEX solutions to achieve investment decisions and stay within budget and time schedules. Further development of ship solutions such as the CO2LOS II Concept B is expected in the future. It is also expected that GHG reducing measures will face an increased profitability in the future as more stringent emission regulations is implemented.

6.6 Import terminal facilities, intermediate storage, and further processing

The two projects aim to use the same import terminal. However, the CO2LOS II project relates to a future phase 2 of the facility able to receive ships exceeding 130 m and handle low pressure CO_2.

7 WP 2 SHIP TECHNOLOGY

The work package studies relevant technologies for ship transport of CO_2 as part of a CCS chain. Loading and unloading at land based facilities has been assumed. Offshore unloading is studied in WP4. Engineering at a conceptual level has been performed for five different ship concepts. The concepts are detailed to a level allowing for an unclassified CAPEX/OPEX estimate at a +/- 35% uncertainty level. A flowchart of the different building blocks is given in Figure 28. Detailed view on Concept B items is relevant also for the other concepts with minor variations.

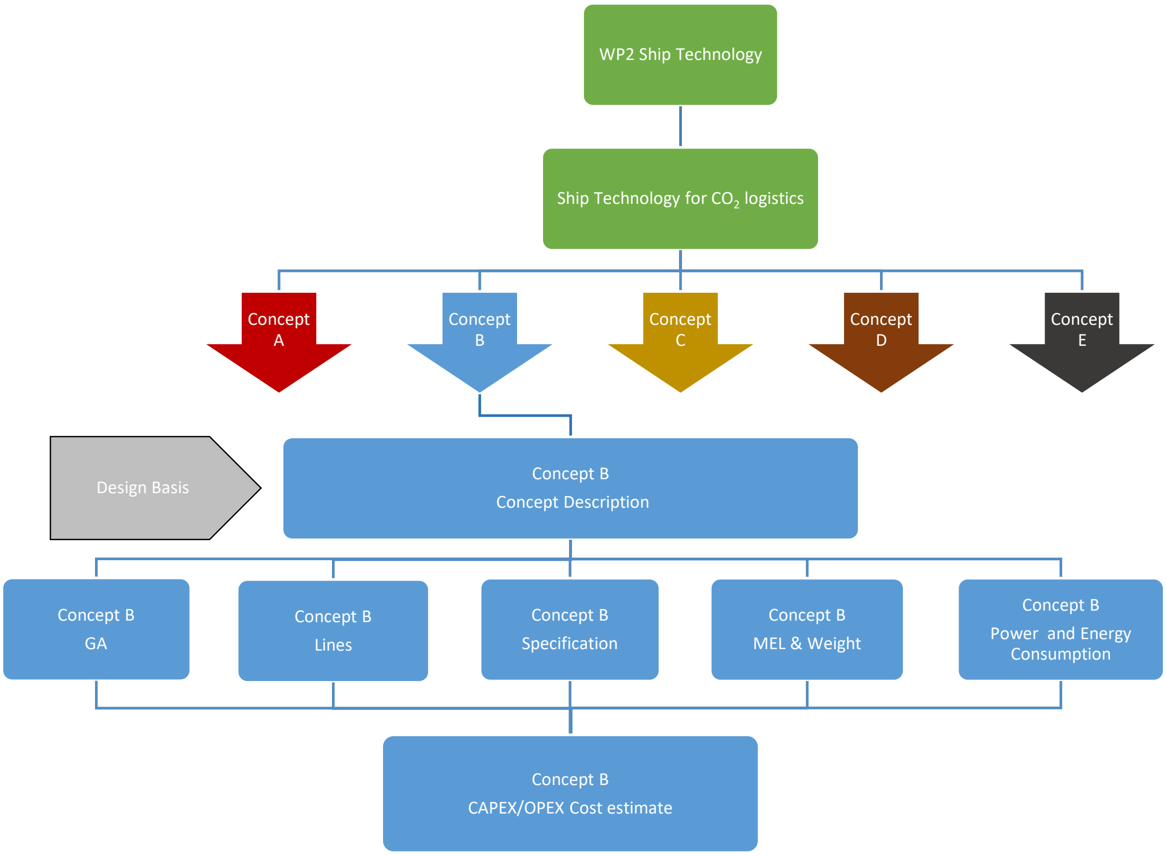


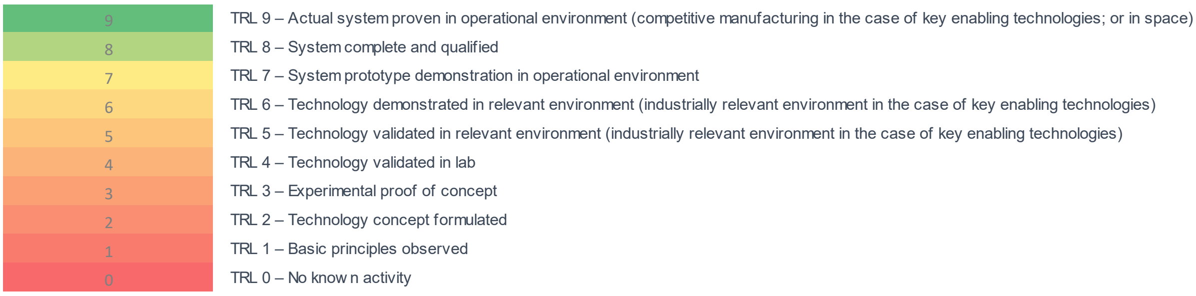
Figure 28 Flowchart WP2

The concepts are based on the cases outlined in chapter 1.2 Design Basis. Concepts A to C are different solutions to the same North Sea base case while Concepts D and E are solutions for respectively trans-Atlantic and European inland and estuary waterways transport. Equally important as the solution itself is the methodology used as it cannot be expected that the concepts will be a perfect fit for a future CCS project. In sum the concepts and the methodology shall serve as a toolbox for CCS projects involving ship transport.

7.1 TRL Study of Ship Technology for CO_2 Transport

An assessment of technologies relevant for carriage of CO_2 by ship as a part of a CCS chain, and the maturity of these technologies in 2019 and 2025 is performed. Note that technologies not used in commercial trade with CO_2 today may still achieve TRL 9 if it is fully commercialised and its function is not connected to the type of cargo carried. Note that only the technical maturity of the solutions is rated. Cost (CAPEX and OPEX) is not a part of the rating although this may disqualify an otherwise sound technological solution.

The TRL (Technological Readiness Level) methodology is based on a definition made by NASA in the 1990's as a means for measuring or indicating the maturity of a given technology. The system is later adopted by ESA and advised by EU for use in EU-funded research and innovation projects. The original system is based on a rating scheme from 1 – 9 where in our context a fully developed and commercialized technology will receive the top rating of 9. A technology where only basic principles have been observed receive the lowest rating of 1. For the purpose of this report, it was found useful to also include a level 0 – no known activity. A colour code is used to visualize the given ratings, and as such improve the understanding of the TRL matrix, ref Figure 29.

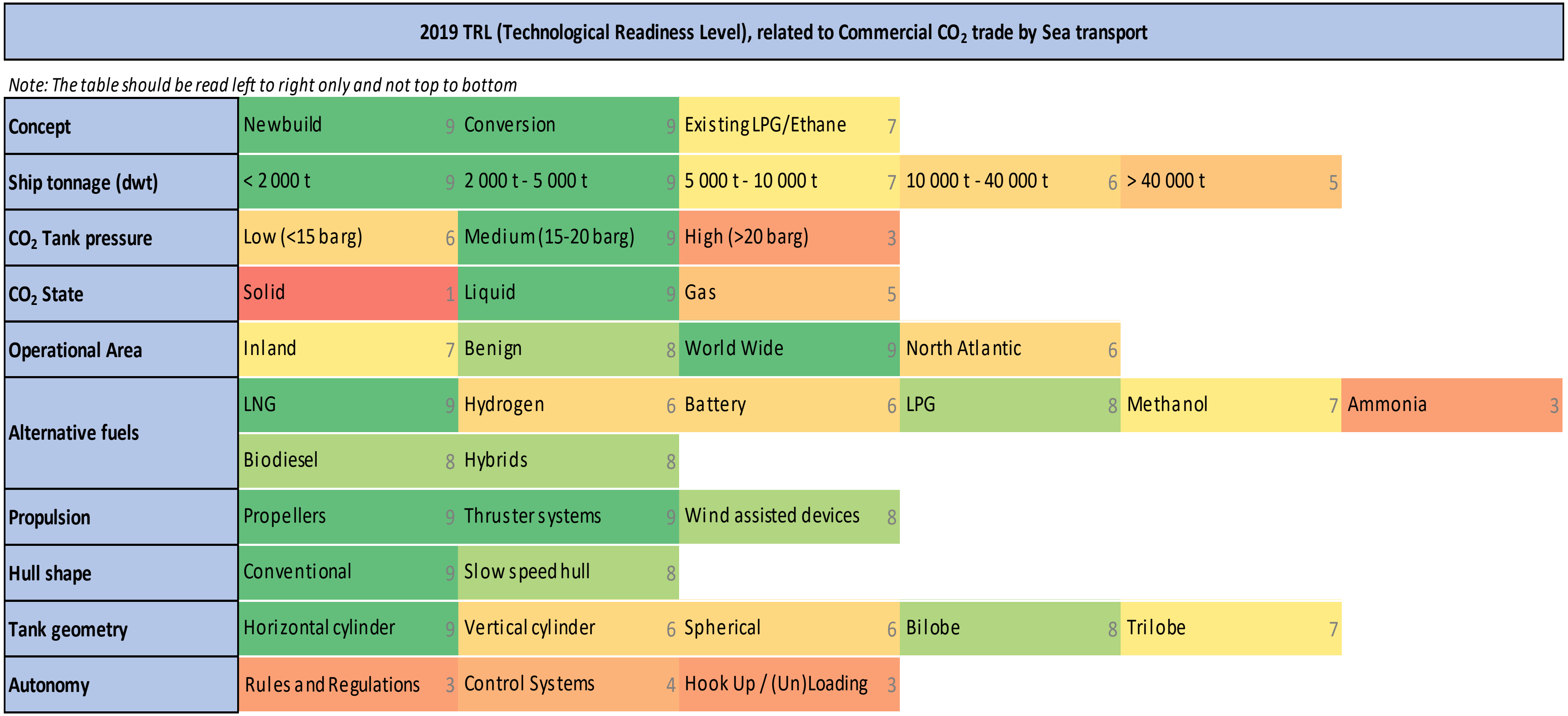


9	TRL 9 – Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)
8	TRL 8 – System complete and qualified
7	TRL 7 – System prototype demonstration in operational environment
6	TRL 6 – Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
5	TRL 5 – Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
4	TRL 4 – Technology validated in lab
3	TRL 3 – Experimental proof of concept
2	TRL 2 – Technology concept formulated
1	TRL 1 – Basic principles observed
0	TRL 0 – No know n activity

Figure 29 TRL scale

The TRL matrix describes the maturity of different technologies related to ship transport as part of a logistics chain for CCS. The described technologies are those found relevant for the 5 concepts within WP2. Ship concepts from WP 4 is not included as technologies related to Offshore Unloading are extensively described in WP 4.

TRL 2019



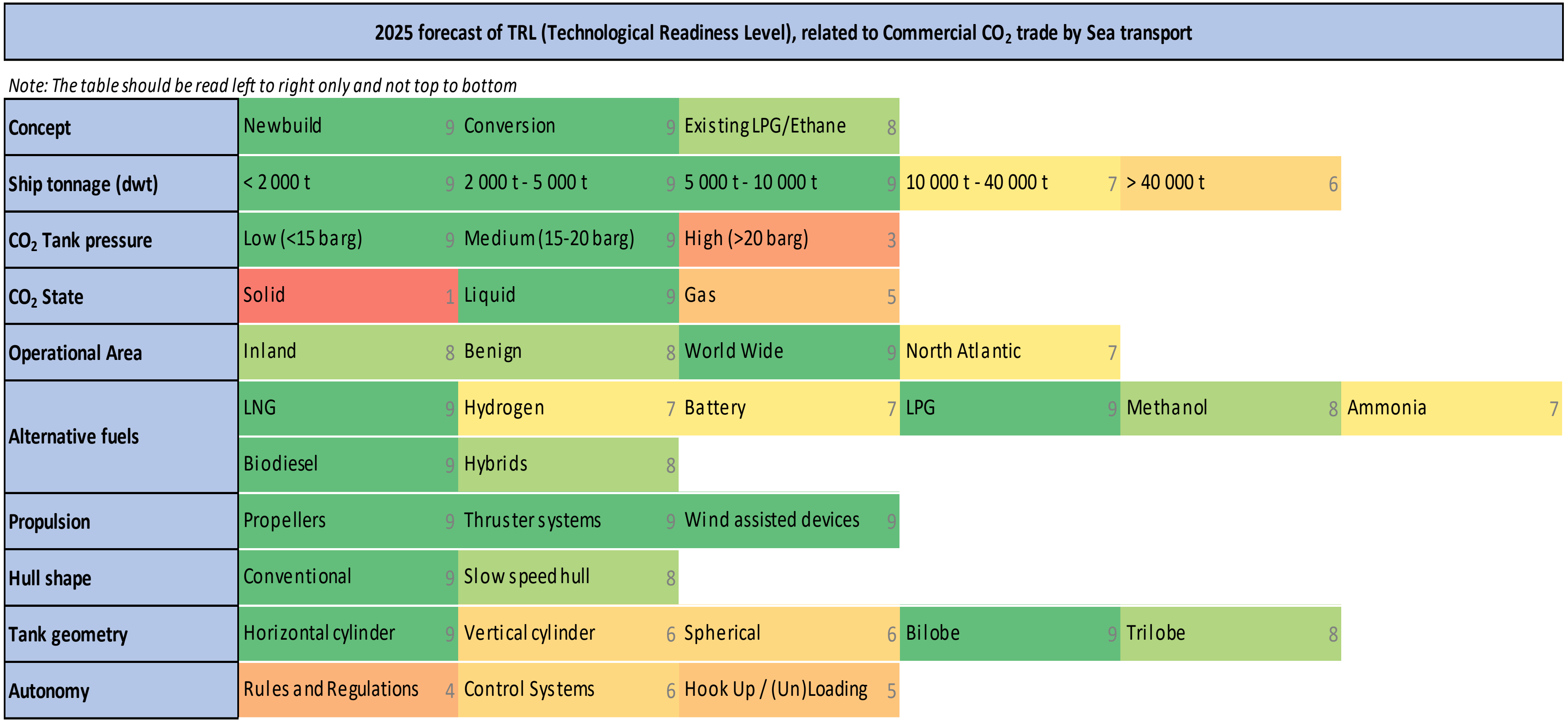
2019 TRL (Technological Readiness Level), related to Commercial CO_2 trade by Sea transport

Note: The table should be read left to right only and not top to bottom

Concept	Newbuild	9	Conversion	9	Existing LPG/Ethane	7						
Ship tonnage (dwt)	< 2 000 t	9	2 000 t - 5 000 t	9	5 000 t - 10 000 t	7	10 000 t - 40 000 t	6	> 40 000 t	5		
CO_2 Tank pressure	Low (<15 barg)	6	Medium (15-20 barg)	9	High (>20 barg)	3						
CO_2 State	Solid	1	Liquid	9	Gas	5						
Operational Area	Inland	7	Benign	8	World Wide	9	North Atlantic	6				
Alternative fuels	LNG	9	Hydrogen	6	Battery	6	LPG	8	Methanol	7	Ammonia	3
	Biodiesel	8	Hybrids	8								
Propulsion	Propellers	9	Thruster systems	9	Wind assisted devices	8						
Hull shape	Conventional	9	Slow speed hull	8								
Tank geometry	Horizontal cylinder	9	Vertical cylinder	6	Spherical	6	Bilobe	8	Trilobe	7		
Autonomy	Rules and Regulations	3	Control Systems	4	Hook Up / (Un)Loading	3						

Figure 30 TRL related to Commercial CO_2 trade by Sea transport (2019)

TRL 2025 – Forecast



2025 forecast of TRL (Technological Readiness Level), related to Commercial CO_2 trade by Sea transport

Note: The table should be read left to right only and not top to bottom

Concept	Newbuild	9	Conversion	9	Existing LPG/Ethane	8						
Ship tonnage (dwt)	< 2 000 t	9	2 000 t - 5 000 t	9	5 000 t - 10 000 t	9	10 000 t - 40 000 t	7	> 40 000 t	6		
CO_2 Tank pressure	Low (<15 barg)	9	Medium (15-20 barg)	9	High (>20 barg)	3						
CO_2 State	Solid	1	Liquid	9	Gas	5						
Operational Area	Inland	8	Benign	8	World Wide	9	North Atlantic	7				
Alternative fuels	LNG	9	Hydrogen	7	Battery	7	LPG	9	Methanol	8	Ammonia	7
	Biodiesel	9	Hybrids	8								
Propulsion	Propellers	9	Thruster systems	9	Wind assisted devices	9						
Hull shape	Conventional	9	Slow speed hull	8								
Tank geometry	Horizontal cylinder	9	Vertical cylinder	6	Spherical	6	Bilobe	9	Trilobe	8		
Autonomy	Rules and Regulations	4	Control Systems	6	Hook Up / (Un)Loading	5						

Figure 31 TRL related to Commercial CO_2 trade by Sea transport, forecast (2025)

7.2 Basis for Technology Selection

The development of CO_2 shipping as a part of a CCS chain should strive to achieve both low GHG footprint and cost-effective solutions to be successful. This is the basis for technology selections made for the different ship concepts. The IMO GHG Strategy describes relevant measures for GHG reduction.

7.2.1 IMO GHG Strategy

As for other ship trades, also the CO_2 trade will need to relate to the IMO vision to phase out GHG emissions as soon as possible within the end of this century. The aim is to reduce total emissions from shipping by 50% in 2050, and to reduce the average carbon intensity by 40% in 2030 and 70% in 2050, compared to 2008. Possible measures for reduction are illustrated in Figure 32, ref (26).

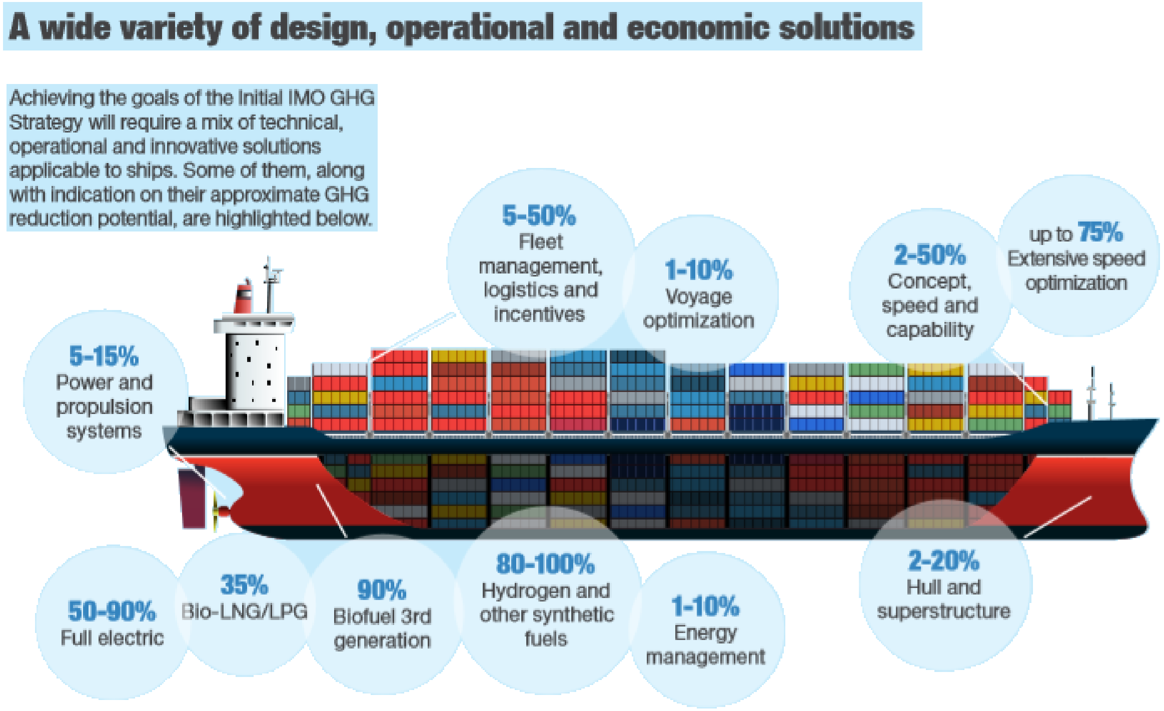


Figure 32 GHG Reduction potential in shipping (IMO), ref. (26)

It is anticipated that the reduction will be motivated by use of information, regulations, economic incentives, and taxes. A selection of current and proposed future schemes such as EEDI, SEEMP, DCS, ETS, MRV, NECA and SECA are listed in the report.

7.2.2 Cost-Effective Solutions

Acknowledging that the Scope of the CO2LOS II project is to reduce the cost of CO_2 ship transportation by utilizing new technology, selection of cost-effective solutions has been a high priority. This is expected to push forward the implementation of CCS by use of ships and create healthy business cases for the operators.

7.3 Key Ship Technology selections

Selection of technologies differ between the logistics cases and also between different concepts for the same case. However, there are some key elements that have been implemented in the concepts where relevant.

- **Low pressure horizontal cylindrical Cargo Tanks for liquid CO_2**
  Low pressure tanks compared to medium pressure as used in current CO_2 ships, allows for reduced steel weight and increased tank diameters. Reference is made to WP6 for further details. The design requires strict operational procedures with respect to pressure control.

- **Tank design within prescriptive Class Rules**
  Tank design has been limited to cylindrical shape with wall thickness of max 40 mm and standard materials. In WP6 this design is verified by use of DNVGL prescriptive Class Rules. Shapes such as bilobe and trilobe and increased wall thickness requires special consideration by Class and are expected to increase building cost and complexity, such tanks may however be a better fit for certain ship sizes. Reference is made to WP8 for further considerations.

- **Slow speed steaming with suitable hull form**
  Optimizing the hull design to suit low service speeds (here in the range of 10 to 12 knots) is an effective measure to reduce fuel consumption and hence operating cost and GHG emissions. The penalty in form of reduced capacity in the logistics chain, is expected to be outweighed by the savings on the increased cost of GHG emissions in the future. If renewable non GHG emission fuels is used, these fuels are considered costly compared to fossil fuels, making fuel saving important even though there are no cost related to any GHG emissions.

- **Wind assisted propulsion by use of Flettner Rotors**
  Reduced GHG emissions and operating cost is also achieved by installation of Flettner rotors. This is mature technology with a potential of significant fuel savings. The technology is further described in the report. Other wind assisted propulsion technologies have also been evaluated.

- **Inshore emission free operation by use of batteries**
  In order to be able to operate with zero emissions when not in open sea and hence meet future port state requirements, batteries are installed to provide enough power for at least one hour at service speed in and out of harbor.

- **Application of (or preparation for) alternative fuels to HFO**
  If available for the required engine size, LNG is used for fuel. Where a Diesel engine is used, a dual fuel type has been selected, able to operate on other fuels such as bio-diesel and bio-gas, and in the future, also converted to ammonia, methanol and hydrogen.

- **Use of VLSFO or LNG to comply with SOx requirements**
  The concepts described in WP2 applies LNG or VLSFO to achieve low Sulphur emissions. This solution is suited to also fit later shift to other sulphur emission free fuels such as hydrogen or ammonia.

- **Low speed 2 stroke engines for fuel efficiency**
  Low speed, 2-stroke engines have higher thermal efficiency and do not require reduction gears with attendant losses in the gearbox. i.e. improved mechanical efficiency compared to medium speed 4 stroke engines. This results in lower fuel consumption.

- **Use of shore power when in harbour**
  The ship shall be equipped with a system for connection to shore power. The system shall be sufficient to avoid any use of the ships engine when in harbour. This is done to reduce GHG emissions.

7.4 The ship concepts of WP 2

Decisions leading to the different ship concepts in WP 2 is visualized in Figure 33.

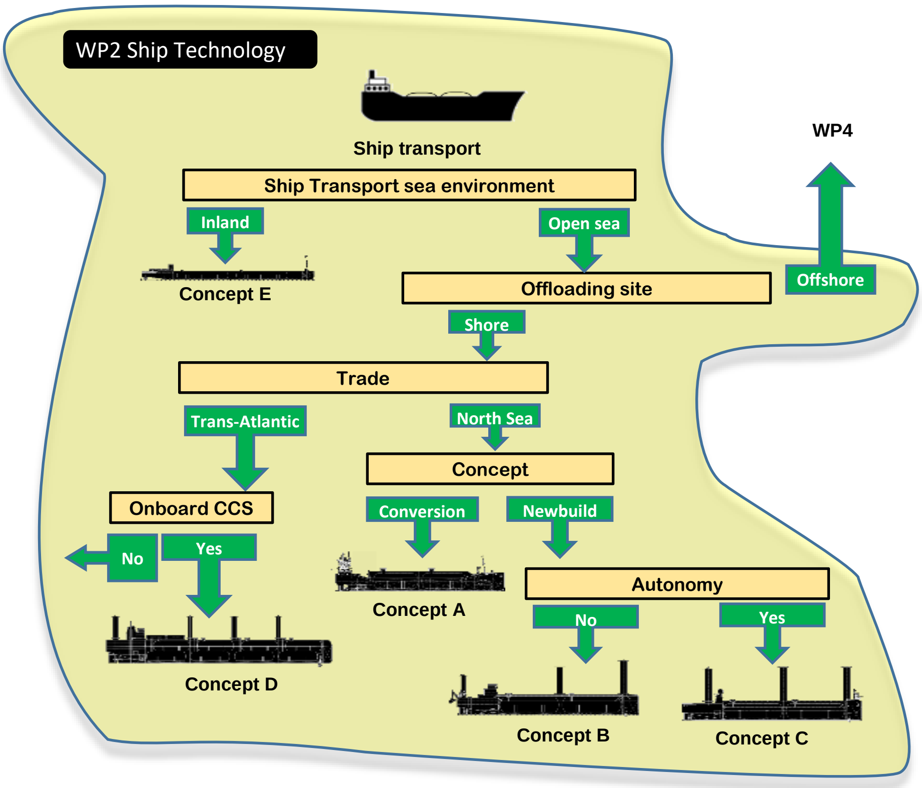


Figure 33 WP2 decision tree for ship concepts

7.4.1 Ship Concepts for the North Sea base case

Ship concepts A, B and C has been developed for the North Sea base case, ref. Table 9. The yearly transport volume of CO_2 is given in the Design Basis. This is the governing parameter when deciding on number of ships in the logistics chain, ship speed, and ship size. Various tools are used for estimation, selection and decisions of logistics, ship main dimensions, weight estimations, tank sizes, equipment selection etc. These are further described within the separate WP 2 report. The entire route is within the North Sea ECA, so emission control is a major priority.

7.4.1.1 Concept A - Ship Conversion based on donor bulk carrier

The ship concept is developed to provide a low CAPEX concept based on proven technology. This will typically be applied in situations where short depreciation periods are required. The concept is a conversion of a MPP type bulk carrier where self-supporting CO_2 tanks will be installed in the cargo holds. The philosophy is to keep the conversion scope of the vessel to a minimum, avoiding major structural modifications, change of engine or change in the watertight compartment configuration. Evaluation of logistics concludes that 4 ships of this size are needed to serve the North Sea logistics case. Reference is made to chapter 7.6 for short specification.

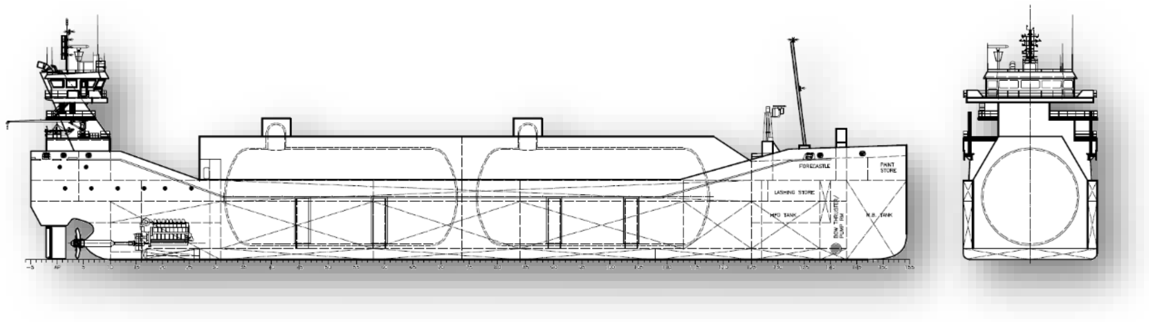


Figure 34 Concept A – Ship Conversion based on donor bulk carrier

7.4.1.2 Concept B – Future Technology Ready Concept

This is a newbuild design CO_2 carrier. The design philosophy is to utilise state of the art solutions for a ship engaged in the transport of CO_2. The selection philosophy favours long term benefits such as HSE issues, time saving and low OPEX. It is also acknowledged that reducing CAPEX is an important selection criterion to achieve realisation of CCS projects. The GHG, NOx and SOx emissions shall be kept at a minimum and comply with current and expected future regulations. Therefore, the vessel shall utilise low emission propulsion systems and be designed to implement emerging technologies as they mature. Due to larger cargo capacity than Concept A, 3 ships are enough to serve the defined logistics chain. Reference is made to chapter 7.6 for short specification.

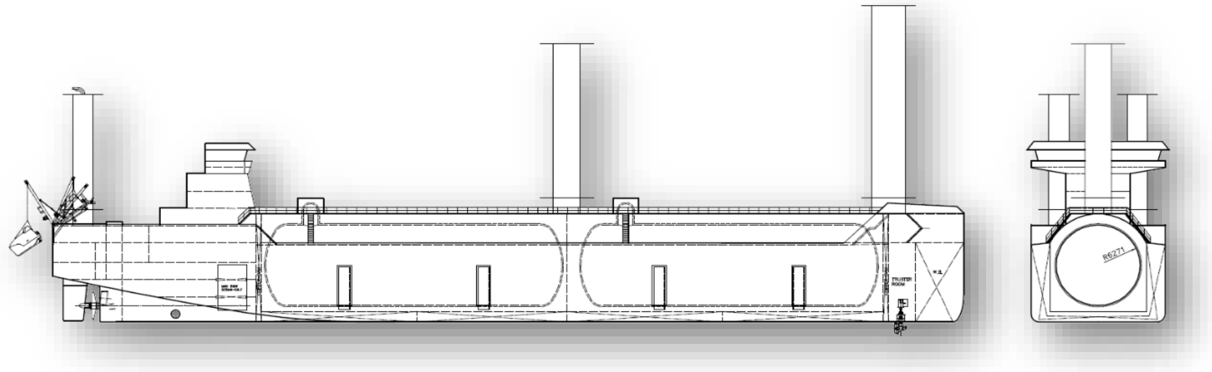


Figure 35 Concept B – Future Technology Ready Concept

7.4.1.3 Concept C - CO_2 Autonomy Concept

This vessel is an autonomous version of Concept B, with the same cargo capacity and speed. Changes are due to the special requirements for autonomous ships. For this design, an autonomous ship is defined as NMA autonomy level 4. This means a ship with no crew onboard but monitored from a remote-control centre. At the present time, there are no rules or regulations for international voyages by autonomous ships, and national projects are still in the pilot project stage, with approval of technology on a case to case basis. The technology for monitoring, control and communication are still under development, and it is expected that especially the communication systems will require further development before autonomous deep-water voyages are feasible. As this project seeks to utilize mature technology, an autonomous vessel is not seen as feasible at this stage. Reference is made to chapter 7.6 for short specification.

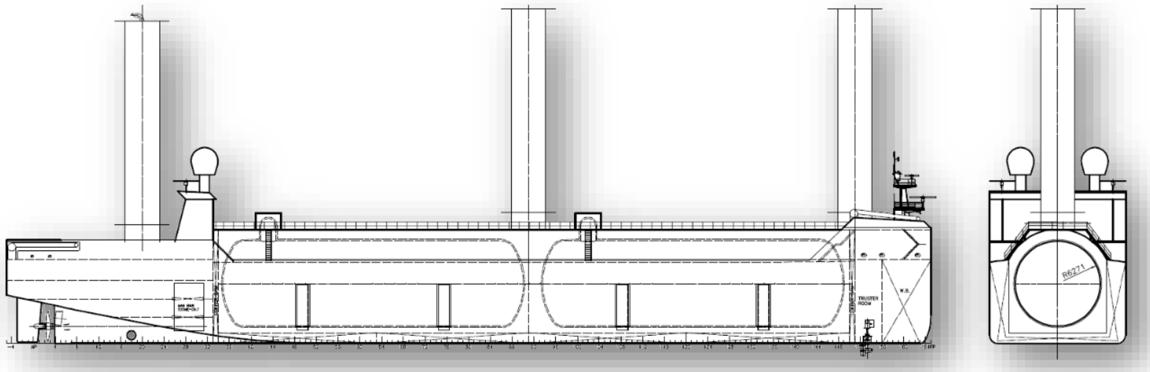


Figure 36 Concept C - CO_2 Autonomy Concept

7.4.2 Ship Concept for the Trans-Atlantic case

The logistics case defined for Concept D is a trans-Atlantic route. The ship transport will be from shore to shore from Rotterdam to the Gulf of Mexico (Port Arthur) as described in Table 11.

7.4.2.1 Concept D – Large Ship Concept

The ship concept is developed to explore technological solutions for CO_2 ship design with relatively large sailing distances and cargo volumes. The CO_2 will be carried in liquid state at low pressure and temperature, max design pressure 7 barg. Tank configuration is based on the cylindrical horizontal tank developed in WP 6. Due to limited size of this tank it is stacked in two levels with the lower level tanks equipped with a rather long tank dome extending above upper deck. Further development towards larger tanks possibly of bilobe or trilobe configuration is recommended for this ship size. The concept is equipped with a system for onboard CCS from the main engine exhaust gas. This is further described in WP7. Evaluation of logistics concludes that 4 ships of this size are needed. Reference is made to chapter 7.6 for short specification.

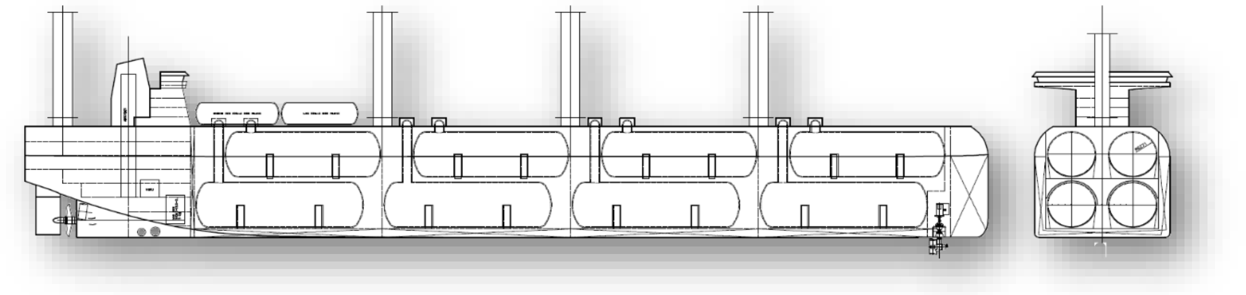


Figure 37 Concept D – Large Ship Concept

7.4.3 Ship Concept for the Estuary and Inland Waterways case

The case is suited for a feeder in the ARA, Zeebrugge and up the Rhine to the Duisburg area. A central hub is assumed in Rotterdam harbor. The case is further described in Table 12.

7.4.3.1 Concept E – Estuary and Inland Waterways

This is a newbuild design of a self-propelled barge for CO_2 transport. The design allows for coastal trade on the Belgian coast down to Zeebrugge and the inland waterways of the Netherlands and Belgian seaboards and also up the Rhine to Duisburg at most water conditions. The size and deadweight are maximized for the area of operation, in order to minimize the fuel consumption and emissions per DWT. The CO_2 will be carried in liquid state at low pressure and temperature, max design pressure 7 barg. However, a medium pressure solution would be rather similar due to the fact that it is not the pressure but rather the regulations that limits the tank diameter. Reference is made to chapter 7.6 for short specification.

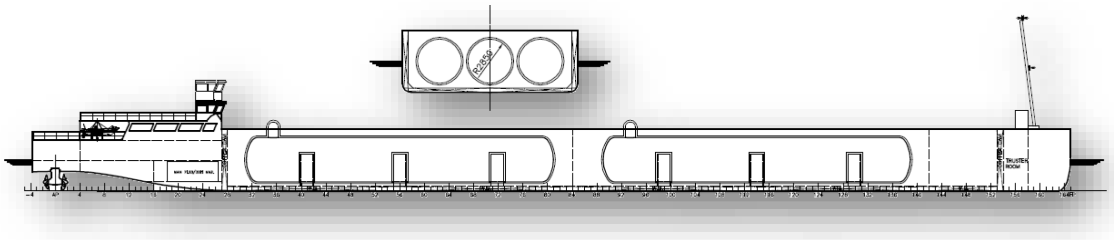


Figure 38 Concept E - Estuary and Inland Waterways

7.5 CAPEX/OPEX

CAPEX and OPEX have been calculated for all concepts for an assumed ship lifetime of 20 years. The uncertainty level is expected to be within +/- 35 % with exception for donor vessel cost (Concept A), autonomy (Concept C) and CCS plant (Concept D). Any comparisons between the concepts should be done with caution since:

- The three logistics cases have different trading route lengths and volumes, and also the selected number of ships vary
- CAPEX cost for the donor ship in Concept A is highly dependent on the market conditions at the time of conversion
- In Concept C, CAPEX cost for autonomy systems is not included due to the lack of commercially available products. Neither is the OPEX cost of a land-based operation centre included. In general, the maturity of an autonomous ship concept for international open sea trade is at a level where a cost estimate is highly uncertain.

CAPEX has been estimated according to the SFI system ref (27). The estimates are based on a combination of weight/cost factors and quotations from suppliers. Quotations from suppliers have been used for all main equipment where weight/cost factors for the SFI group is not applicable. Included in the calculations are +15% contingency for CAPEX and +5% contingency for OPEX. The CAPEX cost for sister ships is assumed to be reduced with 10% for ship 2, 3 etc, mainly due to reduced engineering costs. OPEX has been estimated based on reference projects and other relevant available information. No taxes for emission of GHG to the environment are considered in the calculations of OPEX. It is foreseen that this will be relevant in the future.

7.5.1 Concept A - CAPEX/OPEX

The calculation is relevant for the North Sea base case logistics case with use of 4 ships of type Concept A. Reference is made to Figure 39 for CAPEX and 20 years accumulated OPEX respectively for one and all four ships in million euro. This amounts to a ship transport cost of 11 €/tonnes based on a transport volume of 2.0 Mt/y.

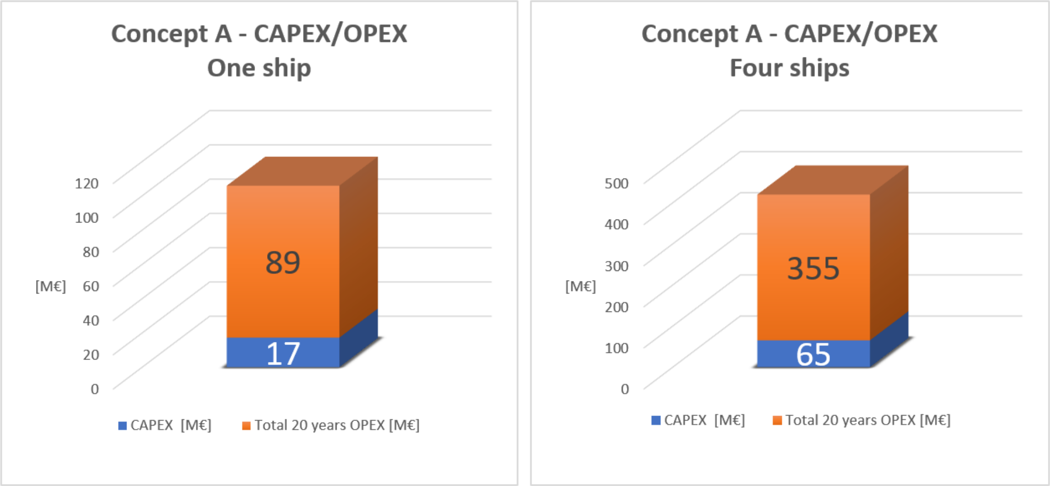


Figure 39 Concept A – CAPEX and OPEX

7.5.2 Concept B - CAPEX/OPEX

The calculation is relevant for the North Sea logistics case with use of 3 Concept B ships. Reference is made to Figure 40 for CAPEX and 20 years accumulated OPEX respectively for one and all three ships in million euro. This amounts to a ship transport cost of 10 €/tonnes based on a transport volume of 2.0 Mt/y.

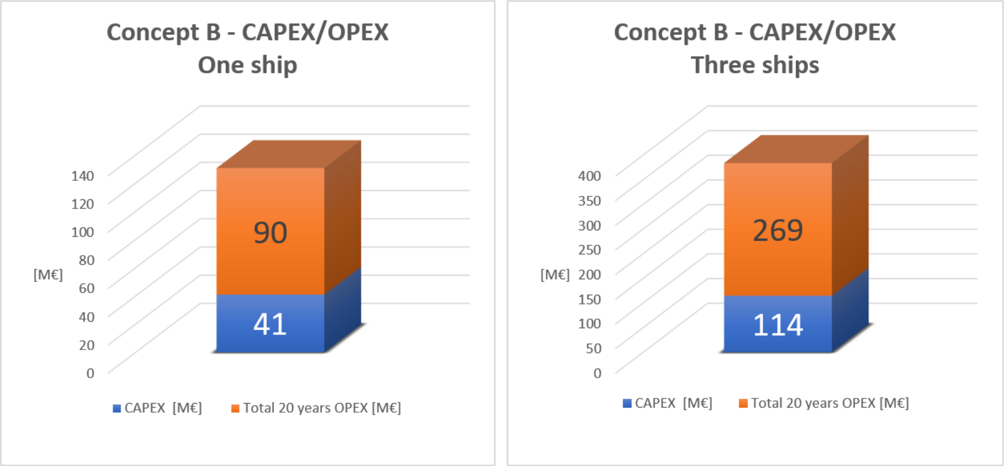
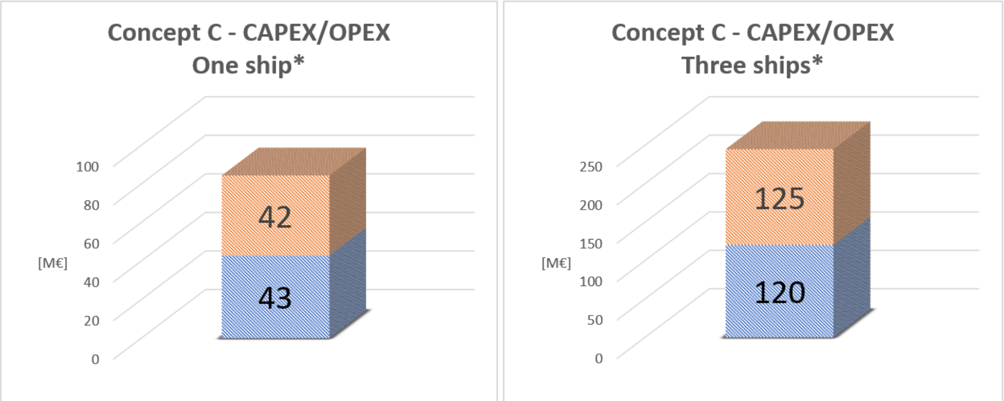


Figure 40 Concept B – CAPEX and OPEX

7.5.3 Concept C - CAPEX/OPEX

The calculation is relevant for the North Sea logistics case with use of 3 Concept C ships. Reference is made to Figure 41 for CAPEX and 20 years accumulated OPEX respectively for one and all three ships in million euro. Note the important items not included in the calculation as described in Figure 41. These items are expected to increase both CAPEX and OPEX significantly. This calculation shall not be considered a +/- 35% cost estimate.



*CAPEX cost for autonomy systems is not included due to the lack of commercially available products. Neither is the OPEX cost of a land-based operation centre included. In general, the maturity of an autonomous ship concept for international open sea trade is at a level where a cost estimate is highly uncertain

*CAPEX cost for autonomy systems is not included due to the lack of commercially available products. Neither is the OPEX cost of a land-based operation centre included. In general, the maturity of an autonomous ship concept for international open sea trade is at a level where a cost estimate is highly uncertain

Figure 41 Concept C – CAPEX and OPEX

7.5.4 Concept D - CAPEX/OPEX

The calculation is relevant for the Trans-Atlantic logistics case with use of 4 Concept D ships. Reference is made to Figure 42 for CAPEX and 20 years accumulated OPEX respectively for one and all four ships in million euro. This amounts to a cost of 18 €/tonnes based on a transport volume of 3.0 Mt/y.

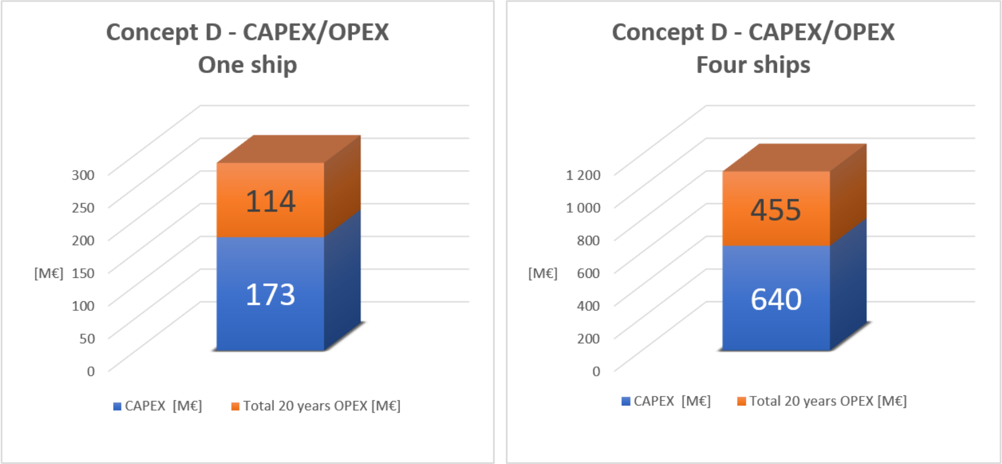


Figure 42 Concept D – CAPEX and OPEX

7.5.5 Concept E - CAPEX/OPEX

The calculation is relevant for the Estuary and Inland Waterways case with use of 4 Concept E ships. Reference is made to Figure 43 for CAPEX and 20 years accumulated OPEX respectively for one and all four ships in million euro.

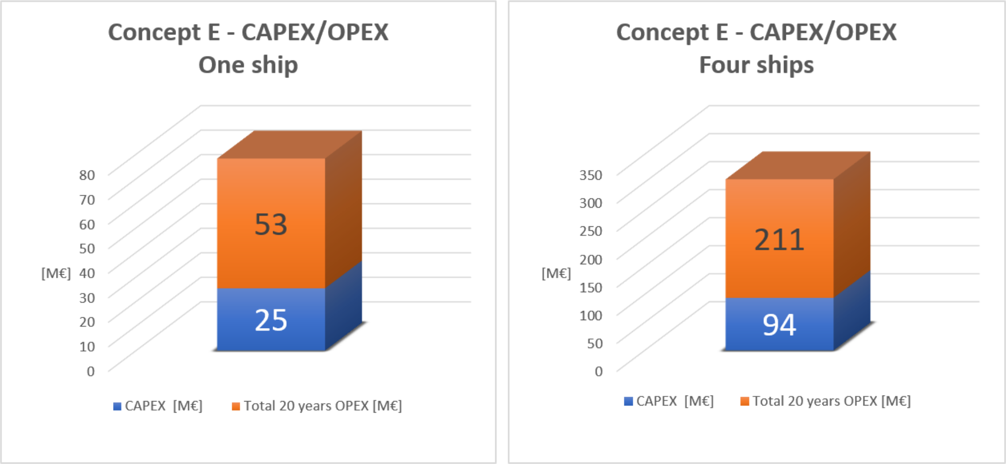
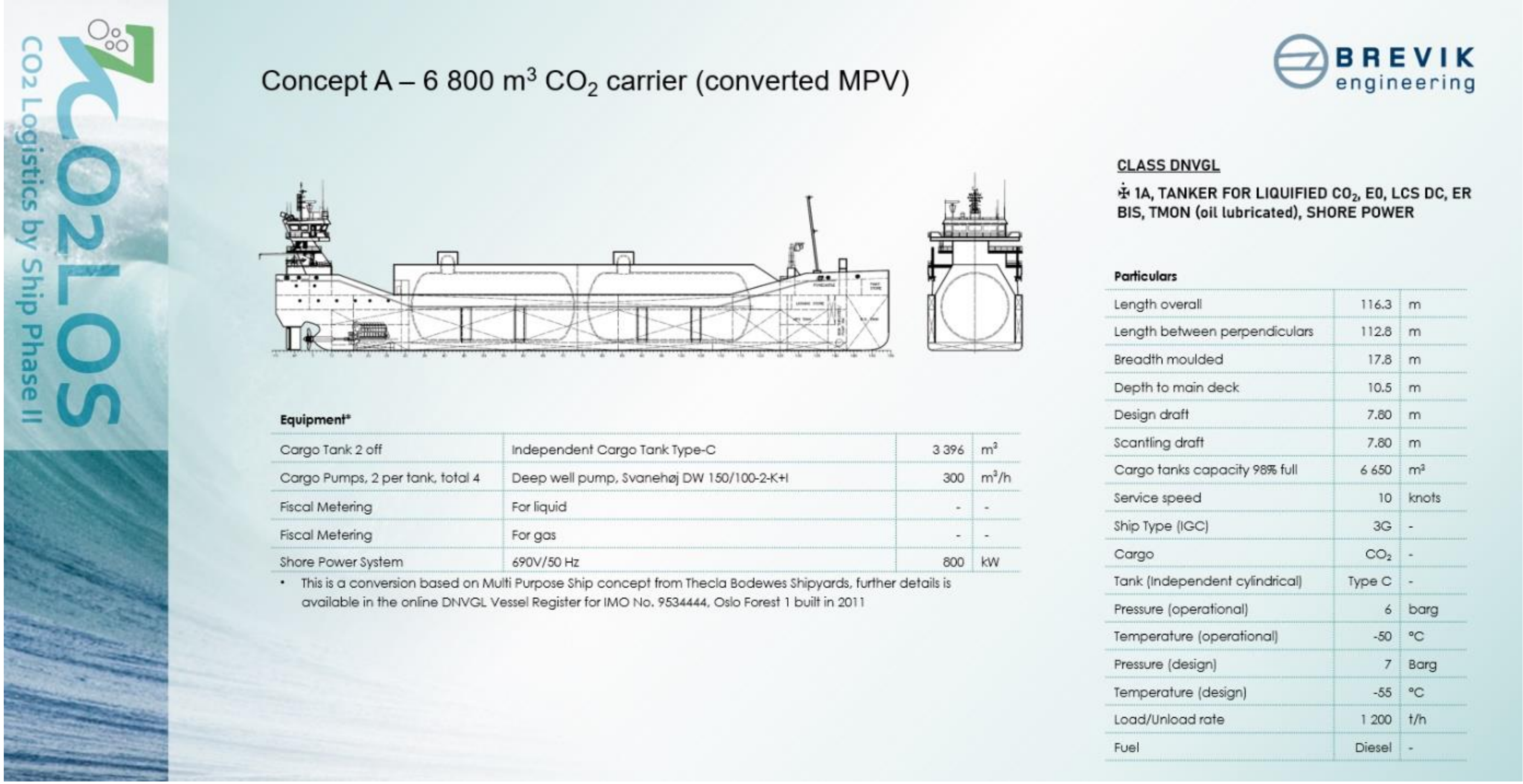


Figure 43 Concept E – CAPEX and OPEX

7.6 Ship concepts short specifications



Concept A – 6 800 m^3 CO_2 carrier (converted MPV)

CLASS DNVGL

✠ 1A, TANKER FOR LIQUIFIED CO_2, E0, LCS DC, ER BIS, TMON (oil lubricated), SHORE POWER

Equipment*

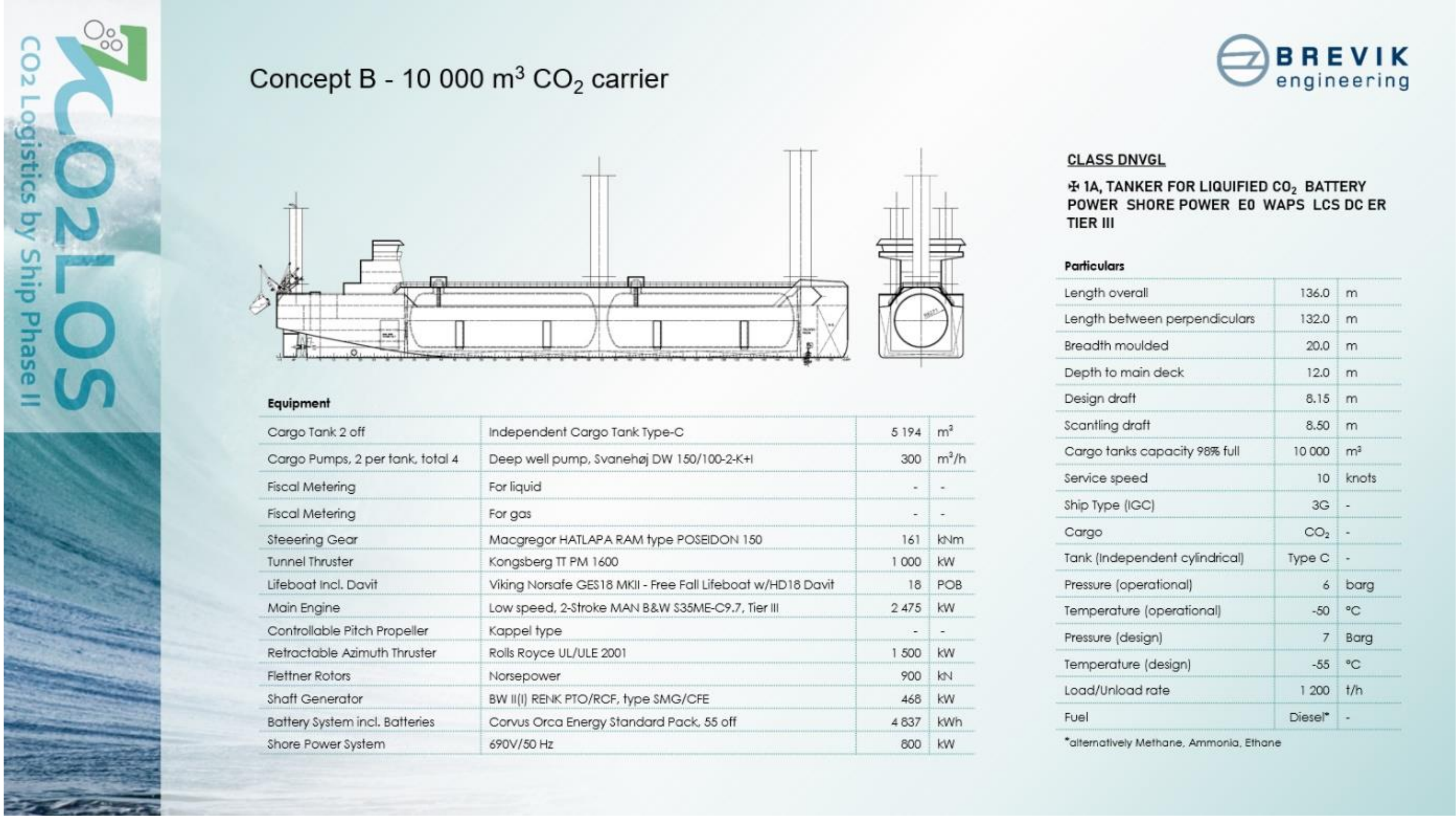
Cargo Tank 2 off	Independent Cargo Tank Type-C	3 396	m^3
Cargo Pumps, 2 per tank, total 4	Deep well pump, Svanehøj DW 150/100-2-K+I	300	m^3/h
Fiscal Metering	For liquid	-	-
Fiscal Metering	For gas	-	-
Shore Power System	690V/50 Hz	800	kW

- This is a conversion based on Multi Purpose Ship concept from Thecla Bodewes Shipyards, further details is available in the online DNVGL Vessel Register for IMO No. 9534444, Oslo Forest 1 built in 2011

Particulars

Length overall	116.3	m
Length between perpendiculars	112.8	m
Breadth moulded	17.8	m
Depth to main deck	10.5	m
Design draft	7.80	m
Scantling draft	7.80	m
Cargo tanks capacity 98% full	6 650	m^3
Service speed	10	knots
Ship Type (IGC)	3G	-
Cargo	CO_2	-
Tank (Independent cylindrical)	Type C	-
Pressure (operational)	6	barg
Temperature (operational)	-50	°C
Pressure (design)	7	Barg
Temperature (design)	-55	°C
Load/Unload rate	1 200	t/h
Fuel	Diesel	-

Figure 44 Concept A – Ship Conversion based on donor bulk carrier



Concept B - 10 000 m^3 CO$_2$ carrier

CLASS DNVGL

✠ 1A, TANKER FOR LIQUIFIED CO$_2$ BATTERY POWER SHORE POWER E0 WAPS LCS DC ER TIER III

Particulars

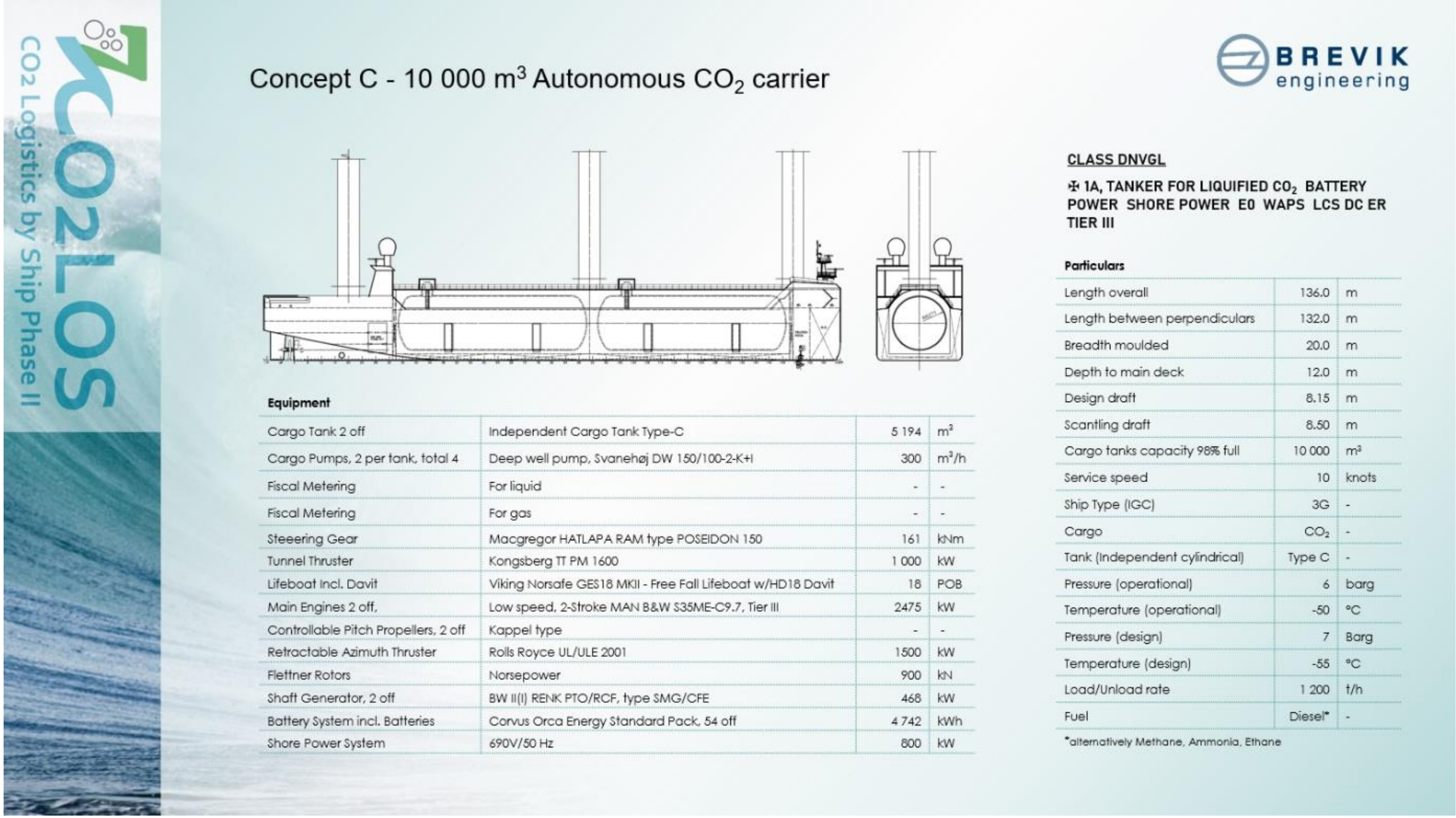
Length overall	136.0	m
Length between perpendiculars	132.0	m
Breadth moulded	20.0	m
Depth to main deck	12.0	m
Design draft	8.15	m
Scantling draft	8.50	m
Cargo tanks capacity 98% full	10 000	m^3
Service speed	10	knots
Ship Type (IGC)	3G	-
Cargo	CO$_2$	-
Tank (Independent cylindrical)	Type C	-
Pressure (operational)	6	barg
Temperature (operational)	-50	°C
Pressure (design)	7	Barg
Temperature (design)	-55	°C
Load/Unload rate	1 200	t/h
Fuel	Diesel*	-

*alternatively Methane, Ammonia, Ethane

Equipment

Cargo Tank 2 off	Independent Cargo Tank Type-C	5 194	m^3
Cargo Pumps, 2 per tank, total 4	Deep well pump, Svanehøj DW 150/100-2-K+I	300	m^3/h
Fiscal Metering	For liquid	-	-
Fiscal Metering	For gas	-	-
Steeering Gear	Macgregor HATLAPA RAM type POSEIDON 150	161	kNm
Tunnel Thruster	Kongsberg TT PM 1600	1 000	kW
Lifeboat Incl. Davit	Viking Norsafe GES18 MKII - Free Fall Lifeboat w/HD18 Davit	18	POB
Main Engine	Low speed, 2-Stroke MAN B&W S35ME-C9.7, Tier III	2 475	kW
Controllable Pitch Propeller	Kappel type	-	-
Retractable Azimuth Thruster	Rolls Royce UL/ULE 2001	1 500	kW
Flettner Rotors	Norsepower	900	kN
Shaft Generator	BW II(I) RENK PTO/RCF, type SMG/CFE	468	kW
Battery System incl. Batteries	Corvus Orca Energy Standard Pack, 55 off	4 837	kWh
Shore Power System	690V/50 Hz	800	kW

Figure 45 Concept B – Future Technology Ready Concept



Concept C - 10 000 m^3 Autonomous CO_2 carrier

CLASS DNVGL

✠ 1A, TANKER FOR LIQUIFIED CO_2 BATTERY POWER SHORE POWER E0 WAPS LCS DC ER TIER III

Equipment

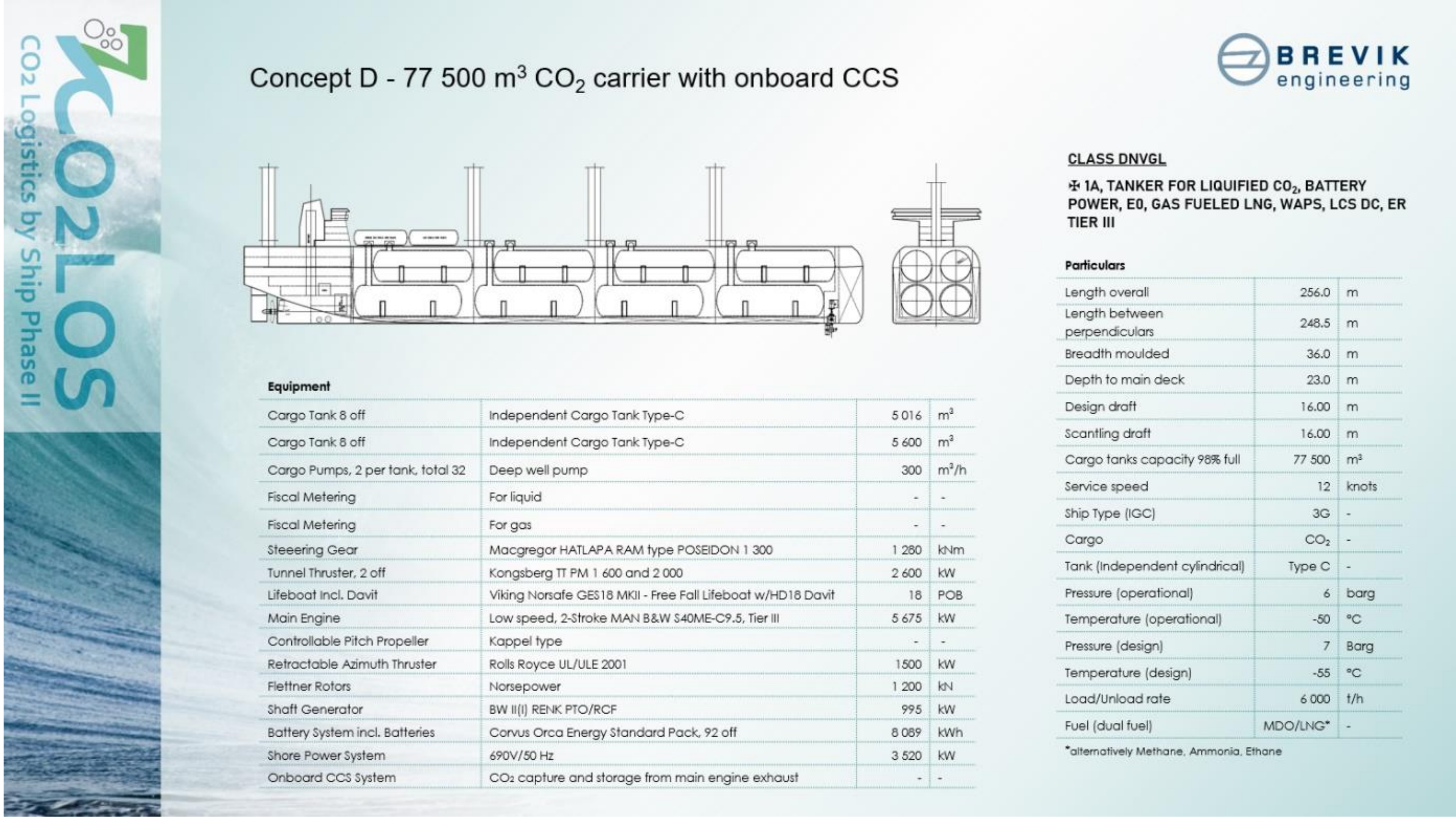
Cargo Tank 2 off	Independent Cargo Tank Type-C	5 194	m^3
Cargo Pumps, 2 per tank, total 4	Deep well pump, Svanehøj DW 150/100-2-K+I	300	m^3/h
Fiscal Metering	For liquid	-	-
Fiscal Metering	For gas	-	-
Steeering Gear	Macgregor HATLAPA RAM type POSEIDON 150	161	kNm
Tunnel Thruster	Kongsberg TT PM 1600	1 000	kW
Lifeboat Incl. Davit	Viking Norsafe GES18 MKII - Free Fall Lifeboat w/HD18 Davit	18	POB
Main Engines 2 off,	Low speed, 2-Stroke MAN B&W S35ME-C9.7, Tier III	2475	kW
Controllable Pitch Propellers, 2 off	Kappel type	-	-
Retractable Azimuth Thruster	Rolls Royce UL/ULE 2001	1500	kW
Flettner Rotors	Norsepower	900	kN
Shaft Generator, 2 off	BW II(I) RENK PTO/RCF, type SMG/CFE	468	kW
Battery System incl. Batteries	Corvus Orca Energy Standard Pack, 54 off	4 742	kWh
Shore Power System	690V/50 Hz	800	kW

Particulars

Length overall	136.0	m
Length between perpendiculars	132.0	m
Breadth moulded	20.0	m
Depth to main deck	12.0	m
Design draft	8.15	m
Scantling draft	8.50	m
Cargo tanks capacity 98% full	10 000	m^3
Service speed	10	knots
Ship Type (IGC)	3G	-
Cargo	CO_2	-
Tank (Independent cylindrical)	Type C	-
Pressure (operational)	6	barg
Temperature (operational)	-50	°C
Pressure (design)	7	Barg
Temperature (design)	-55	°C
Load/Unload rate	1 200	t/h
Fuel	Diesel*	-

*alternatively Methane, Ammonia, Ethane

Figure 46 Concept C - CO_2 Autonomy Concept



Concept D - 77 500 m³ CO_2 carrier with onboard CCS

Equipment

Cargo Tank 8 off	Independent Cargo Tank Type-C	5 016	m³
Cargo Tank 8 off	Independent Cargo Tank Type-C	5 600	m³
Cargo Pumps, 2 per tank, total 32	Deep well pump	300	m³/h
Fiscal Metering	For liquid	-	-
Fiscal Metering	For gas	-	-
Steeering Gear	Macgregor HATLAPA RAM type POSEIDON 1 300	1 280	kNm
Tunnel Thruster, 2 off	Kongsberg TT PM 1 600 and 2 000	2 600	kW
Lifeboat Incl. Davit	Viking Norsafe GES18 MKII - Free Fall Lifeboat w/HD18 Davit	18	POB
Main Engine	Low speed, 2-Stroke MAN B&W S40ME-C9.5, Tier III	5 675	kW
Controllable Pitch Propeller	Kappel type	-	-
Retractable Azimuth Thruster	Rolls Royce UL/ULE 2001	1500	kW
Flettner Rotors	Norsepower	1 200	kN
Shaft Generator	BW II(I) RENK PTO/RCF	995	kW
Battery System incl. Batteries	Corvus Orca Energy Standard Pack, 92 off	8 089	kWh
Shore Power System	690V/50 Hz	3 520	kW
Onboard CCS System	CO_2 capture and storage from main engine exhaust	-	-

CLASS DNVGL

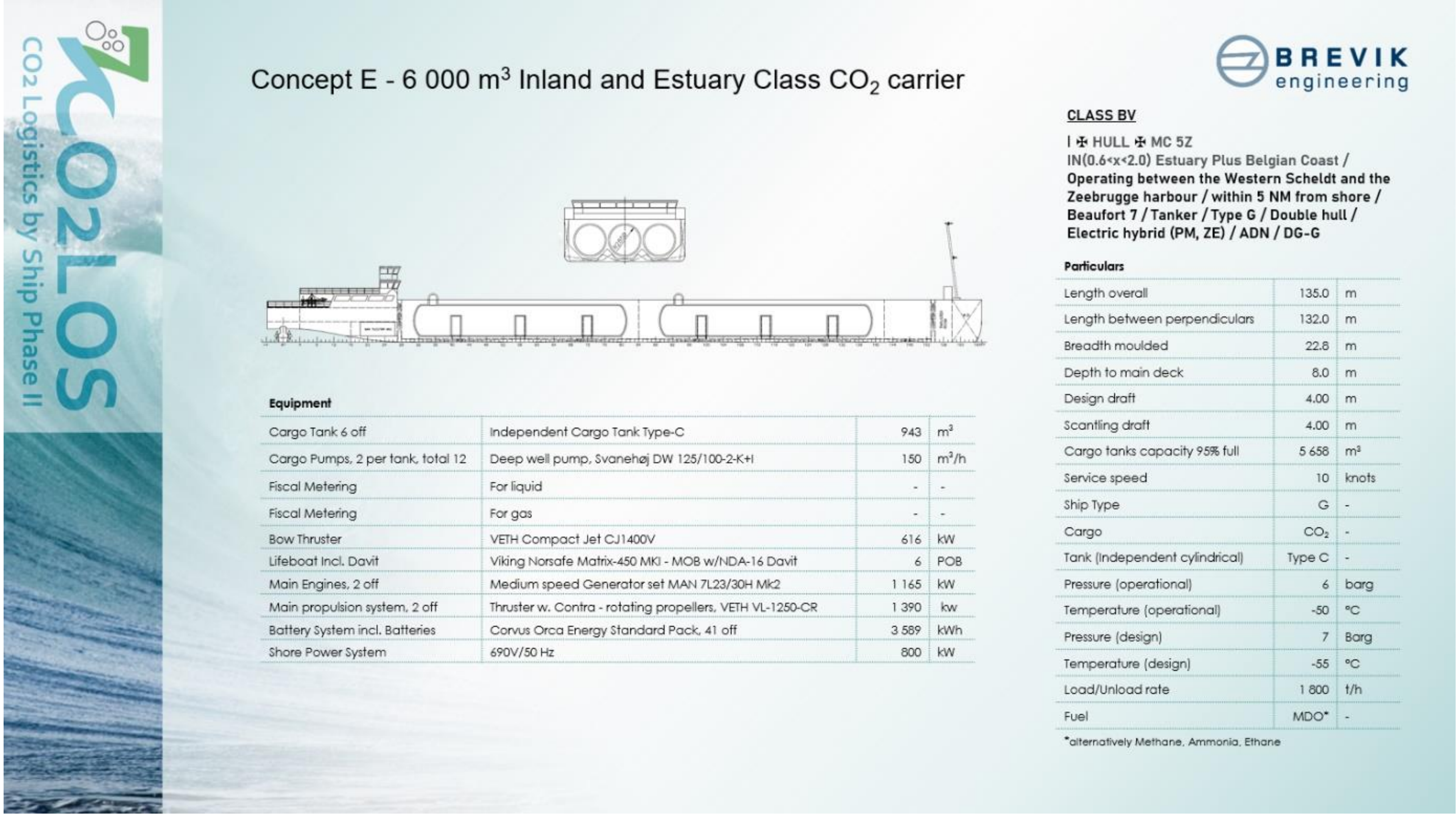
✠ 1A, TANKER FOR LIQUIFIED CO_2, BATTERY POWER, E0, GAS FUELED LNG, WAPS, LCS DC, ER TIER III

Particulars

Length overall	256.0	m
Length between perpendiculars	248.5	m
Breadth moulded	36.0	m
Depth to main deck	23.0	m
Design draft	16.00	m
Scantling draft	16.00	m
Cargo tanks capacity 98% full	77 500	m³
Service speed	12	knots
Ship Type (IGC)	3G	-
Cargo	CO_2	-
Tank (Independent cylindrical)	Type C	-
Pressure (operational)	6	barg
Temperature (operational)	-50	°C
Pressure (design)	7	Barg
Temperature (design)	-55	°C
Load/Unload rate	6 000	t/h
Fuel (dual fuel)	MDO/LNG*	-

*alternatively Methane, Ammonia, Ethane

Figure 47 Concept D – Large Ship Concept



Concept E - 6 000 m^3 Inland and Estuary Class CO_2 carrier

CLASS BV

I ✠ HULL ✠ MC 5Z
IN(0.6<x<2.0) Estuary Plus Belgian Coast / Operating between the Western Scheldt and the Zeebrugge harbour / within 5 NM from shore / Beaufort 7 / Tanker / Type G / Double hull / Electric hybrid (PM, ZE) / ADN / DG-G

Particulars

Length overall	135.0	m
Length between perpendiculars	132.0	m
Breadth moulded	22.8	m
Depth to main deck	8.0	m
Design draft	4.00	m
Scantling draft	4.00	m
Cargo tanks capacity 95% full	5 658	m^3
Service speed	10	knots
Ship Type	G	-
Cargo	CO_2	-
Tank (Independent cylindrical)	Type C	-
Pressure (operational)	6	barg
Temperature (operational)	-50	°C
Pressure (design)	7	Barg
Temperature (design)	-55	°C
Load/Unload rate	1 800	t/h
Fuel	MDO*	-

*alternatively Methane, Ammonia, Ethane

Equipment

Cargo Tank 6 off	Independent Cargo Tank Type-C	943	m^3
Cargo Pumps, 2 per tank, total 12	Deep well pump, Svanehøj DW 125/100-2-K+I	150	m^3/h
Fiscal Metering	For liquid	-	-
Fiscal Metering	For gas	-	-
Bow Thruster	VETH Compact Jet CJ1400V	616	kW
Lifeboat Incl. Davit	Viking Norsafe Matrix-450 MKI - MOB w/NDA-16 Davit	6	POB
Main Engines, 2 off	Medium speed Generator set MAN 7L23/30H Mk2	1 165	kW
Main propulsion system, 2 off	Thruster w. Contra - rotating propellers, VETH VL-1250-CR	1 390	kw
Battery System incl. Batteries	Corvus Orca Energy Standard Pack, 41 off	3 589	kWh
Shore Power System	690V/50 Hz	800	kW

Figure 48 Concept E - Estuary and Inland Waterways

7.7 HSE issues related to CO_2 ship transport

CO_2 transport by ship has been performed in a smaller scale for decades and is as such a mature technology where the related HSE issues should be well known and documented.

7.7.1 Human exposure

The CO_2 is carried in liquid form at temperatures down to -50°C. Human contact with the liquid and cooled structures shall be avoided to prevent frost burns.

If released from the tank the liquid cargo will transform to a gas. CO_2 is a colourless gas, odourless at standard concentrations, but with an unpleasant odour at higher concentrations. The gas is both asphyxiating and it does also have toxic effects. Human exposure at increasing concentrations is described in Table 23. Similar apply to all breathing life forms.

Table 23 Human symptoms vs CO_2 concentration in air, ref (28)

Concentration in air	Symptoms
1 %	Slight increase in breathing rate
2 %	Breathing rate increases to 50 % above normal level. Prolonged exposure can cause headache, tiredness.
3 %	Breathing increases to twice normal rate and becomes laboured. Weak narcotic effect, impaired hearing, headache, increase in blood pressure and pulse rate.
4 % – 5 %	Breathing increases to approximately four times normal rate; symptoms of intoxication become evident and slight choking may be felt
5 % – 10 %	Characteristic sharp odour noticeable. Very laboured breathing, headache, visual impairment, and ringing in the ears. Judgment may be impaired, followed within minutes by loss of consciousness.
10 % – 15 %	Within a few minutes' exposure, dizziness, drowsiness, severe muscle twitching, unconsciousness.
17 % – 30 %	Within one minute, loss of control, unconsciousness, convulsions, death
>50 %	Unconsciousness occurs more rapidly above 10 % level. Prolonged exposure to high concentrations may eventually result in death from asphyxiation.

Gas detectors need to be in place to raise alarm when the CO_2 concentration in air reaches the limit of 0.5%. The molecular weight of carbon dioxide is 44 which is heavier than air. CO_2 will therefore accumulate and replace air at low points. The ship should be designed to the extent possible to avoid creating wells and pockets where a leakage of CO_2 can be trapped, especially in areas accessed by the crew.

A dispersion analysis should be made, covering both the ship and the surroundings and the risk for human exposure for large releases connected to i.e. a tank rupture.

7.7.2 Environmental exposure

CO_2 released to the environment will not have an environmental impact at these volumes for single incidents. As soon as the CO_2 is diluted in water or the air it will not pose a danger. On the other hand, GHG emission from cargo and engines should of course be avoided in a larger climate perspective.

7.8 WP 2 Conclusions

- There is **not one optimal ship concept** and size for CO_2 transport. For each unique CCS case, many factors need to be evaluated. This report provides three CCS cases with five ship concepts and the methodology behind, which can be used as a toolbox for future CCS developments.
- **Low pressure and hence larger tanks,** low temperature, and higher cargo density results in more efficient ship designs, typically from ship sizes where a medium pressure ship would have to shift from one to two tanks in the breadth of the ship. For inland vessels where the tank size is limited by regulations, the advantage of low pressure is not as obvious. The narrow operating margin to the triple (freezing) point is regarded as the main challenge of low pressure. Low pressure CO_2 transport is currently not at a TRL 9.
- **GHG reductions** must be implemented in future ship design to achieve the goals of the international community and to avoid implementation or effect of costly emission schemes in the future. Within this report several GHG emission reducing measures are discussed and implemented in the ship concepts. It should be noted that measures such as wind assisted propulsion and slow steaming are mature technology with a potential GHG emission reduction matching or exceeding that which can be achieved by conversion to LNG as fuel.
- **CAPEX and OPEX** calculations have been done for all ship concepts assuming a lifetime of 20 years. The results could be used as input to case studies involving ship transport of CO_2. The assumptions and basis for the calculations should be carefully observed to be able to use the numbers correctly. The importance of OPEX as a part of the lifetime cost increases with decreasing ship sizes, mainly due to number of crew members being rather constant.
- **The autonomous concept** is found to be at a low TRL and not realistic in the near future (5-10 years). This applies both to the technical solutions and the regulatory framework. The potential for such a ship is however undisputable. Elimination of crew cost and hence removal of one important obstacle for implementation of slow steaming is the obvious advantage. A direct effect is less GHG emissions but indirectly the need for less power may also open for use of batteries or other zero emission solutions. However, the IMO required minimum propulsion power to maintain the maneuverability of ships in adverse conditions must still be fulfilled, possibly by use of hybrid solutions.
- **Inland operation** on European waterways requires a dedicated ship design for efficient operation. Such a ship will have to relate to strict draft and air draft requirements and a limitation on cargo tank size of 1000 m^3. This is not realistic for an ocean-going ship. This suggest a feeder system of self-propelled barges arriving at coastal hubs where from the CO_2 can be transported further to the storage location.
- **Conversion** of a bulk ship or similar to a CO_2 carrier as outlined for Concept A, could be a feasible solution. One main issue that may be decisive is the cost and availability of the donor vessel. Also, the possibility of meeting current and future emission regulations with an old vessel should be carefully evaluated.
- **A large ship solution**, here typically around 80 000 t of CO_2 is not a mature design as of today. The tank shape, size and arrangement need to be further investigated and developed. Concept D must be regarded as an early sketch of such a concept where especially the two tank layers and the long tank domes from the lower layer should be subject to further work. Also, further development of a possible onboard CCS system must be done to mature the solution.

8 WP 12 CARBON LIMITS DATABASE

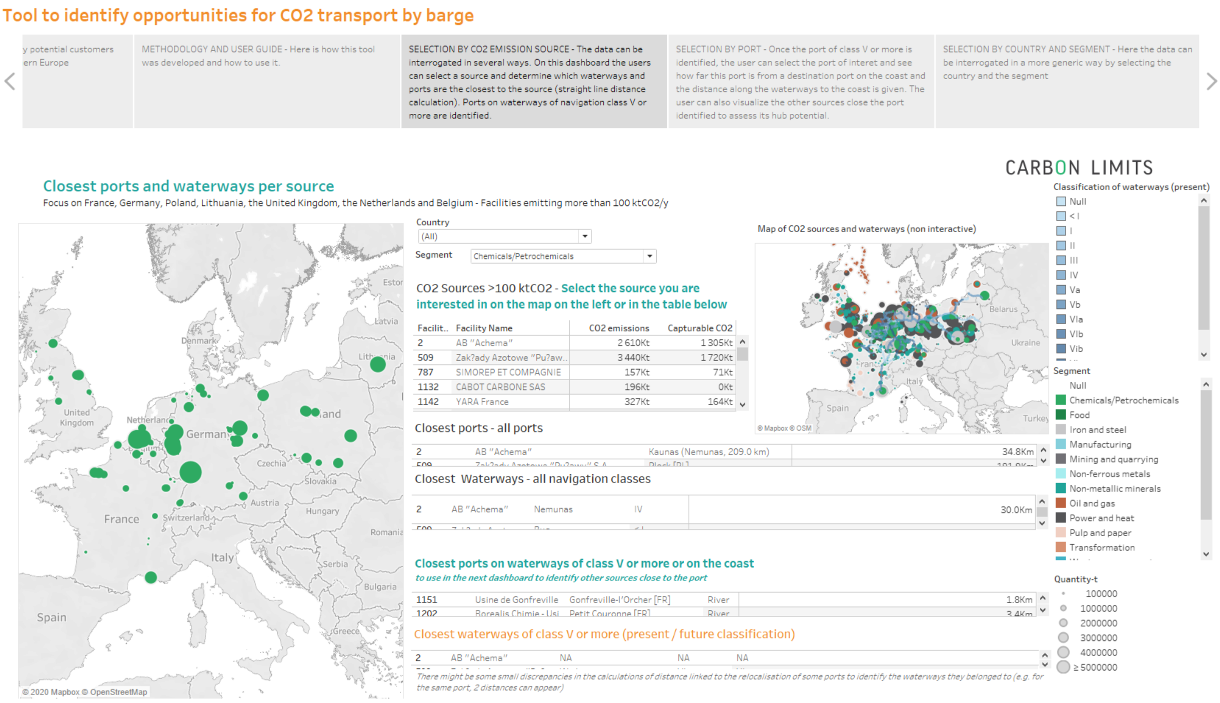
8.1 Program description

This work package is a software tool to identify opportunities for CO_2 transport by barge. The tool is developed by Carbon Limits, ref. (29). The tool's main features are:

- Identification and classification of the waterways in continental Europe where barges can navigate
- Identification of the CO_2 sources along these waterways

Typical user options are:

- Selection of an emission source to determine the closest ports and waterways
- Selection of a port on a waterway of class V or more, and find the CO_2 sources around, the port of destination on the coastline and the paths towards this port and filter on the distance to the port
- Selection of a country and a segment
- Looking at the main CO_2 Hubs
- Identifying the opportunities for the barge Concept E design in WP2



Tool to identify opportunities for CO2 transport by barge

y potential customers
ern Europe

METHODOLOGY AND USER GUIDE - Here is how this tool was developed and how to use it.

SELECTION BY CO2 EMISSION SOURCE - The data can be interrogated in several ways. On this dashboard the users can select a source and determine which waterways and ports are the closest to the source (straight line distance calculation). Ports on waterways of navigation class V or more are identified.

SELECTION BY PORT - Once the port of class V or more is identified, the user can select the port of interet and see how far this port is from a destination port on the coast and the distance along the waterways to the coast is given. The user can also visualize the other sources close the port identified to assess its hub potential.

SELECTION BY COUNTRY AND SEGMENT - Here the data can be interrogated in a more generic way by selecting the country and the segment

Closest ports and waterways per source

Focus on France, Germany, Poland, Lithuania, the United Kingdom, the Netherlands and Belgium - Facilities emitting more than 100 ktCO2/y

Country: (All)
Segment: Chemicals/Petrochemicals

Map of CO2 sources and waterways (non interactive)

CO2 Sources >100 ktCO2 - Select the source you are interested in on the map on the left or in the table below

Facilit..	Facility Name	CO2 emissions	Capturable CO2
2	AB "Achema"	2 610Kt	1 305Kt
509	Zak?ady Azotowe "Pu?aw..	3 440Kt	1 720Kt
787	SIMOREP ET COMPAGNIE	157Kt	71Kt
1132	CABOT CARBONE SAS	196Kt	0Kt
1142	YARA France	327Kt	164Kt

Closest ports - all ports

2	AB "Achema"	Kaunas (Nemunas, 209.0 km)	34.8Km

Closest Waterways - all navigation classes

2	AB "Achema"	Nemunas	IV	30.0Km

Closest ports on waterways of class V or more or on the coast

to use in the next dashboard to identify other sources close to the port

1151	Usine de Gonfreville	Gonfreville-l'Orcher [FR]	River	1.8Km

Closest waterways of class V or more (present / future classification)

2	AB "Achema"	NA	NA	NA

There might be some small discrepancies in the calculations of distance linked to the relocalisation of some ports to identify the waterways they belonged to (e.g. for the same port, 2 distances can appear)

Figure 49 Screen dump of one of the program features

9 WP 7 CO_2 CAPTURE ONBOARD

The International Maritime Organization (IMO) reported in 2012, that the global shipping industry was responsible for a significant percentage (3.1%) of total global CO_2 emissions representing ~940 Mt of CO_2 annually. Further, IMO has projected that these emissions will rise by 50 – 250% towards 2050 unless mitigating actions are implemented. Therefore, IMO has in 2018 adopted an initial strategy on reduction of GHG emission from ship and the ambition is to reduce the GHG emission from ships by at least 50% by 2050 compared to the 2008 level.

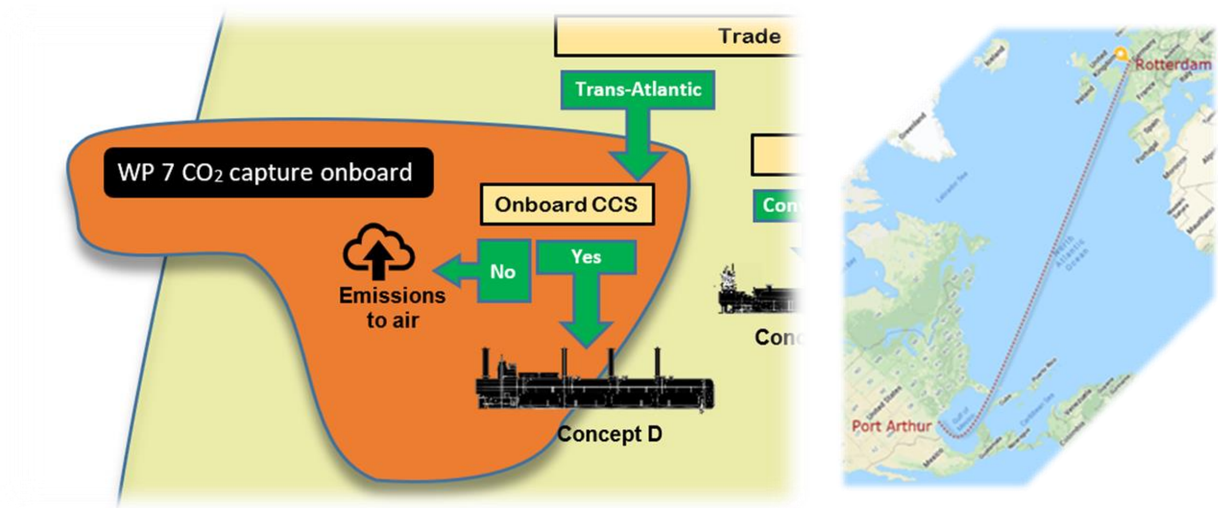


Figure 50 WP 7

Zero emission shipping options rely on the use of electricity, wind power or alternative fuels, such as hydrogen or ammonia. However, that requires major modifications to the ships and the logistics of fuel distribution. An alternative or addition to these measures is CO_2 capture on board the ship, which is the focus of WP 7. The base case for this work has been the concept D ship, shore to shore from Rotterdam to the Gulf of Mexico (Port Arthur) as described in Table 11 and illustrated in Figure 50.

The work has been divided into four main parts:

- Technology screening
- Implementation of CO_2 capture on the ship
- Waste heat availability
- Feasibility study of onboard CO_2 capture and handling

9.1 Technology screening

The CO2LOS onboard capture concept aims at capturing CO_2 from the engines of a CO_2 transport ship. The captured CO_2 is compressed, liquefied, and stored on the ship for further transport to an injection site for permanent underground storage. Figure 51 illustrates the overall concept.

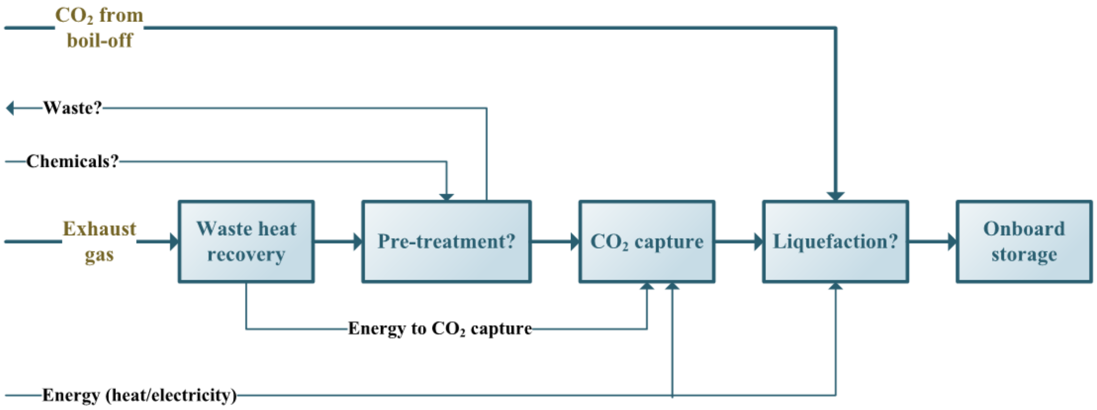


Figure 51 Overall concept for onboard CO_2 capture and handling.

The available capture technologies can be divided in in three main categories:

1. Absorption processes
2. Membrane processes
3. Solid adsorbent processes

Chemical absorption is the most mature process and is based on CO_2 absorption in amine and a stripping process to release the captured CO_2. Waste heat is used for regeneration of the amine absorbent.

There are some challenges for the installation onboard a ship as movement and tilt of the packed columns of the onboard capture plant could represent a potential challenge causing maldistribution of gas and liquid in the column packed bed. Prior knowledge suggests that the capture rate suffers from permanent tilt, and drops drastically if the inclination exceeds 1°, but that the drop in capture efficiency appears to be less if the motion occurs harmoniously around the centre line of the column. Column liquid/gas maldistribution might be less of a problem for smaller scale columns at hand in the CO2LOS II capture case and could likely be mitigated with structured plate packings, shorter columns, or additional liquid distributor internals. For severe weather conditions with rough sea, tilt could still represent a problem for the conventional packed beds.

The membrane processes are based on CO_2 selective membranes. The driving force for the process is partial pressure and differences in permeability for the different chemical species. The achievable CO_2 purity is between 70% and 90% per stage, so more stages are needed.

Solid adsorbent processes utilize selective adsorption of CO_2 on a solid adsorbent. When the adsorbent is saturated with CO_2, regeneration is needed. This regeneration can be done by pressure or temperature swing, but anyhow this requires energy.

The TRL assessment looking into the most likely TRL in 2025, concluded that the absorption process was the best alternative.

An initial assessment of the adsorption technology from Svante Inc. have been performed and the conclusion here was that this technology required a too large area to be suitable on board a ship.

9.2 Implementation of CO_2 capture in the ship

Feed streams have been assessed with respect to flow, impurities, CO_2 concentration and temperature. The possible effect of NOx and SOx on the chosen amine-based absorption process have been explored. A process layout and a preliminary MEL (Master Equipment List) has been developed and the conclusion is that installing an amine-based capture plant in the concept D ship is feasible.

In Figure 52, the 35 m tall absorber and the storage tank for reclaimed CO_2 is shown integrated in the vessel general arrangement drawing. The stripping tower can be placed in the vicinity of the absorber, but this is not a requirement.

The height of the absorber tower is not decided, but a maximum of 35 m is assumed for illustrating the worst case for installation. The figure shows that for the concept D, it is possible to integrate the CO_2 capture plant in the ship.

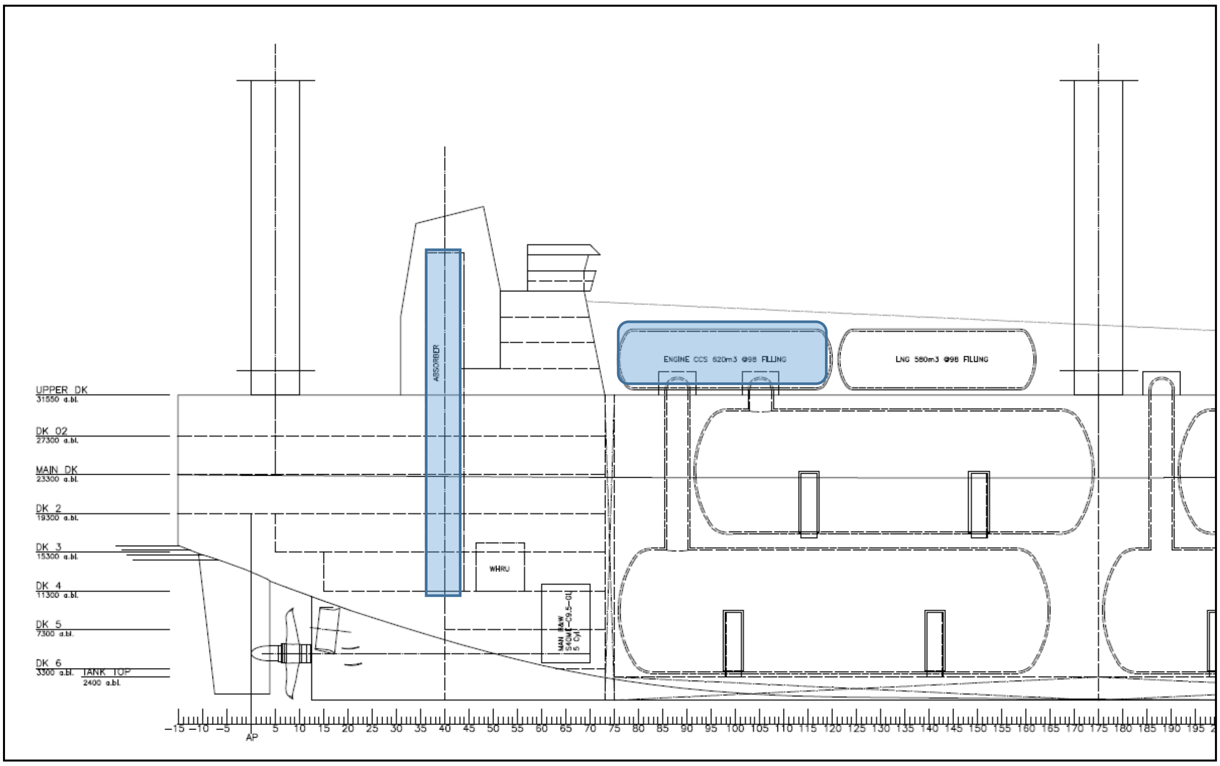


Figure 52 Integration of absorber in the concept D-ship

To avoid adverse effects from the movement due to the sea, the packed columns, the absorber and the stripper should be placed as close as possible to the centreline.

9.3 Waste heat availability

The sources of waste heat on ships in general and concept D in detail have been explored. Due to the temperature needed in the CO_2 capture process, the scavenge air temperature and the engine cooling water temperature is too cold to be used directly as heat source in the capture process.

The temperature requirement for the capture process is 120°C and it is assumed that 30°C is needed as driving force for the heat exchange.

The usable waste heat amounts to 0.8 – 1.4 GJ/tonnes CO_2 released.

For a capture rate in the area of 80-90% the energy requirement is 4 GJ/tonnes CO_2. For these calculations MEA is used and liquefaction is not included. The liquefaction plant and storage for the reclaimed CO_2 have been sized based on the liquefaction plant in WP3.

The absorber flue gas fan work and the compression work in the liquefaction is included as part of the parasitic load. Solvent circulation was not included but is expected to be of minor importance. The liquefaction dominated the parasitic load

Thus, more heat is required. Possible remedies are:

1. One can reduce the fraction of CO_2 captured, say to 50%
2. One can burn extra fuel in an afterburner to provide the additional heat.
3. A properly placed heat pump could be considered, upgrading low temperature waste heat or as cooling in an amine absorption tower. Mechanical work must then be provided. Analysing such options is outside the current scope.

9.4 Feasibility study on onboard CO_2 capture and handling

An assessment of options for onboard absorption-based CO_2 capture has been performed to provide the basis for the development of a concept for onboard capture including energy supply, and onboard CO_2 storage. An overall assessment of energy balances for cases of process flowsheets including ship engine, WHRU, flue gas afterburner, CO_2 capture, compression and liquefaction were performed in addition to initial size estimations of main units of the CO_2 capture process.

The following key design parameters have been included in the assessment:

- CO_2 capture ratio: 50 – 90%
- Absorber packing height: 5 – 20 m
- Engine fuel type: diesel or LNG

The boundary conditions for the assessment has been:

- Nominal engine load: 66% of max engine load
- Engine type (linked to fuel type): MAN B&W S40ME-C9.5-GI, 5-cylinder L1. 5675 kW

The following key performance parameters have been evaluated:

1. Added fuel consumption due to capture. Both thermal and electrical parasitic load is considered.
2. Height and footprint of the main capture process units.

Extra fuel for an afterburner is needed to provide sufficient energy even if the capture rate is reduced to 50%. This is true both with diesel and LNG as fuel.

At 90% capture the fuel penalty is 6-9% for LNG operation and 9-12% for diesel operation. The reason for the higher number with diesel is the increased CO_2 quantity.

9.5 Conclusion

Based on an evaluation of the available technologies performed by study of literature and discussions with experts in SINTEF and a TRL (Technology Readiness Level) analysis, the amine-based absorption technology is recommended.

The waste heat from the exhaust is the only heat stream with sufficient temperature to be of direct use as process heating for the CO_2 capture process. The amount of heat available falls short of the requirement for the capture process.

At capture rates above 50%, burning additional fuel in an afterburner is therefore required. The quantity of extra fuel varies with the capture rate chosen and the fuel burned. This highest number is 12% extra fuel when running on diesel and having a capture rate of 90%.

A preliminary sizing of the largest equipment has been performed and the conclusion is that installing a CO_2 capture plant based on the most mature amine technology in the ship concept D is feasible.

Even though the amine technology for CO_2 capture is the most mature technology, it seems that such technology is not available off the shelf for installation on a ship.

10 WP 9 MULTIPURPOSE USE OF SHIP

Both the possibility of carrying another cargo on the return voyage and applying the ship to another trade when no longer engaged in CO_2 transport has been investigated.

The main motivation for investigating possible return cargoes in combination with CO_2 is to improve the profitability of the trade and such accelerate CCS by use of ships.

The status of multi-gas ships has been investigated by means of literature study and the conclusion is that there are no ships in operation today carrying CO_2 and alternative return cargo.

Liquid CO_2 is heavier than water, this means that for the majority of other gases the transport and offloading capacity (tonnage) will be reduced due to their lower density. LPG and CO_2 are traditionally seen as compatible, nevertheless the requirements for the ship design and cargo systems differ.

The requirements for alternative gases have been explored. LNG has not been included due to the low boiling point temperature at the pressure used for CO_2 transportation. Focus have been on the low pressure transport in this report as this has been the base case of the CO2LOS II project. The gases explored have compatible or higher boiling point temperature than CO_2 at 7 barg.

In WP 9, ref (11) a large number of gases has been evaluated. Here only the requirements for Ethane, Ethylene, Propane, Propylene, Butylene and Butane cargo has been included together with CO_2.

10.1 Requirements for CO_2

There are several design criteria that are unique for CO_2 cargo handling:

- Pressure safety valves: 4 PSV's are required for each cargo tank. As the PSV may clogged by dry ice, a valve is required upstream the safety valve so that an uncontrolled depressurisation can be stopped. These shall close at least 0.5 bar above the triple point of the actual cargo loaded.
- No inert gas plant is installed on board.
- Only ship type 3G is required which is the least stringent standard for gas carrier.

Table 24 shows some of the special requirements for ships transporting CO_2.

Table 24 Requirements for ships carrying CO_2, ref. (18)

Parameter	Requirement
Ship type	3G (the other ship types can be used)
Tank size	Not limited by special requirements
Tank type	Independent cargo tank type C. Kept above triple point pressure at all times, except during inspection.
Inert gas plant	Not required
PSV	4 per cargo tank, two in operation and possibility for easy shut-off. The discharge piping shall be free from obstructions and no protective screens shall be fitted
ESD	At pressure at minimum 0.5 bar above the triple point, all inlets and outlets shall be shut off
Pressure surveillance	Visible and audible alarm is required
Piping	All connections to be installed above main deck. No flanges in cargo holds
Pump	Deepwell pump required, fitted in dome on tank. Pump seal as for hydrocarbons
Gas detectors	Continuous monitoring is required where CO_2 can accumulate. Audible and visual alarms shall be located at the bridge, the cargo and engine control room

10.2 Requirements for Ethane, Ethylene, Propane, Propylene, Butylene and Butane

Below the special requirement for ethane, ethylene, propane, propylene, butylene, and butane is listed. There are no special requirements regarding tank sizes and materials. An inert gas plant is required because the compounds are all flammable. The density, see Table 25, is much lower than CO_2 and less cargo will therefore be carried and the offloading rate will be lower measured in t/h.

Table 25 Special designs required for ethane, ethylene, propane, propylene, butane, butylene, ref. (18)

Special designs required for ethane, ethylene, propane, propylene, butane, butylene	
Ship type	2G, for butane 2PG in addition
Tank size	Not limited by special requirements
Tank type	If pressurized above 0.7 barg, independent tank type C
Inert gas plant	Required
Vent mast	For venting of flammable gases
PSV	As for pressure vessels
Piping	No special requirements
Cargo pump	Deepwell pump required, fitted in dome on tank.
Level measurement	Indirect closed
Vapor detection	Flammable vapor
Reliquefication plant	Need is depending on length of trade and insulation

10.3 General for return cargo

Operating with return cargo will increase cost and complexity of the trade. This must be balanced with the increased income from the return cargo and the reduced CO_2 footprint for the CO_2 trade as the return voyage is a laden voyage.

- Onshore/port facilities must be able to deliver and receive the return cargo in addition to the CO_2 cargo
- Roundtrip time will increase due to necessary cleaning of tanks and additional time for loading and unloading
- HSE requirements may increase due to more stringent requirements for the return cargo
- Finding favourable logistics scenarios for the given ship type, size and number of ships is more challenging

10.4 Conclusion

It can be concluded that hydrocarbon compounds such as ethane, propane, ethylene, propylene, butane, and pentanes are the best candidates for return cargo, due to few extra requirements. It should be noted that the Northern Lights ships are planned to be combined LPG/ CO_2 ships, however not with return cargo.

11 WP 4 OFFSHORE UNLOADING

WP 4 describes relevant ship logistics scenarios with offshore unloading and injection of CO_2. Injection condition to the well is assumed to be 70 barg and 0°C to a harsh weather North Sea location at approximately 200 m water depth, ref. Table 10. As a reference for environmental parameters the Gullfaks field was chosen (30). WP 10 looks further into the limiting parameters for connecting to the offshore unloading systems. Also, the cost development when going to larger volumes of CO_2 is explored.

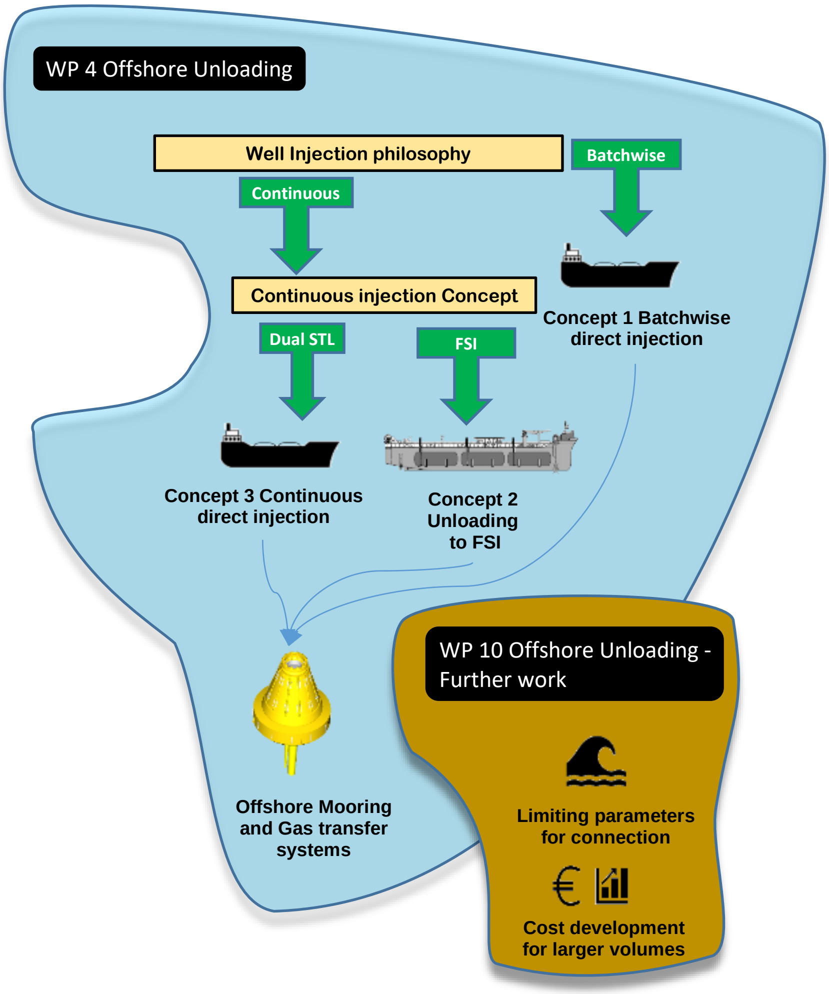


Figure 53 WP 4 and WP 10

The Offshore unloading has been approached following three main concepts of transport of about 1.8 Mt/y low pressure liquid CO_2 from Rotterdam to the Offshore location:

1. Batchwise injection directly from shuttle tankers (two off) to reservoir, through onboard pre-treatment facilities. Connection to wells via one SAL system.
2. A single shuttle tanker with Offloading to one Floating Storage and Injection unit (FSI) for pre-treatment and continuous injection. Connection to wells via one STL system.
3. Two shuttle tankers with onboard pre-treatment plants. Overlapping connection to wells via 2 STL systems allowing for continuous injection.

General selection tools for offshore unloading supporting the choices of gas transfer system, mooring system, logistics and concept for the FSI is included and utilised for selection of the above concepts.

11.1 Concept 1 - Offshore Unloading by Batchwise Direct Injection

The concept is based on a shuttle tanker equipped with a pre-treatment plant. For offloading a BLS is mounted on the ship which can be connected to a SAL system for injection to the well. The systems are shown in Figure 54. For connection to the SAL system a criterion of Hs 4.5 m is used. This criterion gives an availability of 92% for the chosen site. As an input to the logistics chain analysis the connection limit is used. Estimates indicate the cost to be 16 €/t which is the cheapest option. However, batchwise injection may not be suitable for all reservoirs.

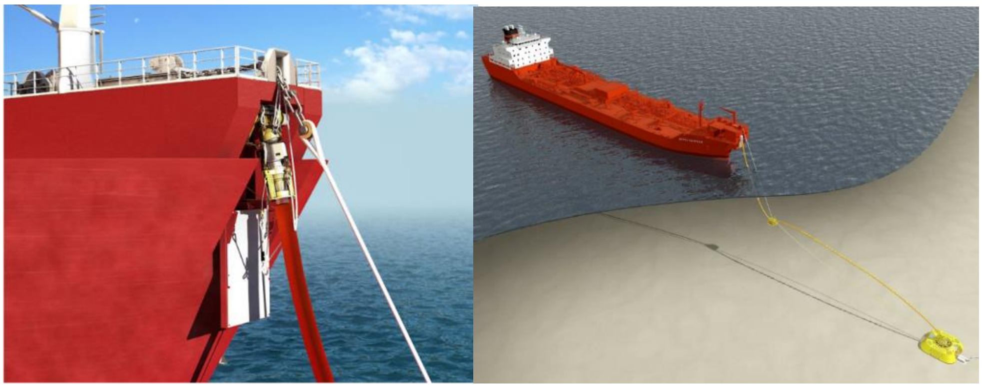


Figure 54 BLS and SAL systems for direct injection

Based on a study of ship sizes and the logistics chain a two ship solution is selected. The main parameters of the tanks and the ship are presented in Table 26 and Table 27 below. The ship's main dimensions are primarily calculated for cost calculations and will need further refining to suit an optimal hull shape. This also applies for the other concepts.

It should be noted that a major part of the cost in a CCS logistics chain is connected to the final storage with drilling of the well(s). Batchwise injection will leave the well(s) idle between shipments of cargo and may prove to give a unacceptably low well utilisation. Well cost calculations are not part of this project.

Table 26 Tank parameters direct injection

No of tanks [-]	Length of tank [m]	Steel weight of tank including support [t]	Total volume in tanks [m^3]
6	34.1	542	27296

Table 27 Main dimension of ship for direct injection

Block coefficient [-]	Displacement [t]	Length between perpendiculars [m]	Breadth [m]	Draught [m]	Depth [m]
0.80	43029	152.7	35.1	10.0	17.0

11.2 Concept 2 - Offshore Unloading to FSI

The concepts consist of a shuttle tanker with CO_2 unloading to a ship-shaped Floating Storage and Injection unit, FSI. The shuttle tanker is equipped with BLS and DP, but no pre-treatment equipment. The BLS is shown in Figure 54 and the DP system is shown in Figure 55. The limit for connection is the same as for Concept 1 i.e. Hs 4.5 m, which gives 92% availability. When screening the wave data from 1958 until today the longest period when it is not possible to connect is 19 days. These 19 days are used as one of the parameters for sizing the FSI. The study of ship size and logistics cases shows that one shuttle tanker is the preferred solution for this concept. The main parameters for the tanks and the shuttle tanker are shown in Table 28 and Table 29. Estimates indicate this to be the most expensive option with a cost of 19 €/t. A sensitivity calculation was done to analyse the effect of making the FSI unmanned. Cost dropped from 19 €/t to 16 €/t. This is the cheapest option if continuous injection is required.

Table 28 Tank parameters shuttle tanker to FSI

No of tanks [-]	Length of tank [m]	Steel weight of tank including support [t]	Total volume in tanks [m^3]
6	38.1	592	30802

Table 29 Main dimension of shuttle tanker to FSI

Block coefficient [-]	Displacement [t]	Length between perpendiculars [m]	Breadth [m]	Draught [m]	Depth [m]
0.80	48310	164.9	35.1	10.4	17.5

The FSI is equipped with an SDS for receiving CO_2 and a STL for injection to the well and for station keeping.

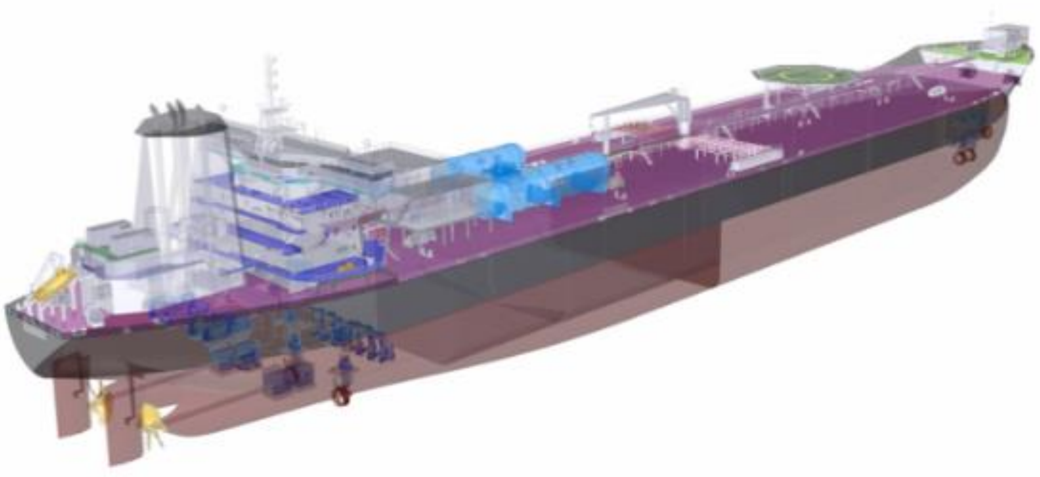


Figure 55 DP system with separated redundant drive lines of propeller, engines, control systems, etc

The FSI injects the CO_2 into the well via a STL system as shown in Figure 56.

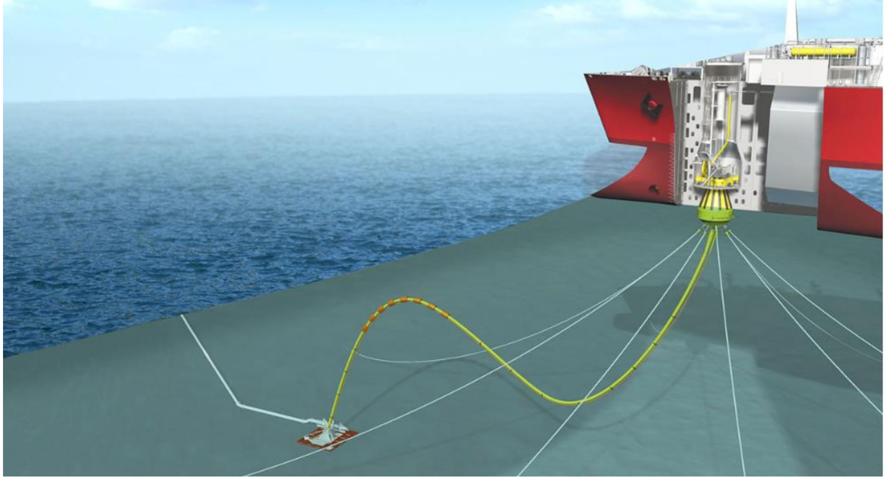


Figure 56 STL system

The FSI has a 6-tank solution for storage and a pre-treatment plant for pre-treatment of the CO_2 before injection to the well. The tank layout is shown in Figure 57 and relevant parameters are presented in Table 30 and Table 31. As seen in the layout the STL is placed in the bow. The SDS is placed in the aft of the FSI. The offloading from the shuttle tanker to the FSI will be done in tandem.

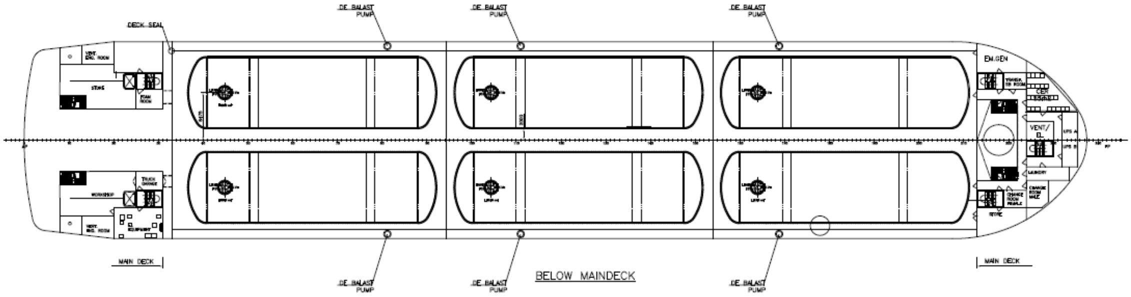


Figure 57 Tank arrangement FSI

Table 30 Tank parameters of FSI

No of tanks [-]	Length of tank [m]	Steel weight of tank including support [t]	Total volume in tanks [m^3]
6	44.2	667	35994

Table 31 Main dimension of FSI

Block coefficient [-]	Displacement [t]	Length between perpendiculars [m]	Breadth [m]	Draught [m]	Depth [m]
0.86	56534	189.6	35.2	9.6	20.0

A summary of the process plant is presented in chapter 11.4.

11.3 Concept 3 - Offshore Unloading by Continuous Direct Injection

The concept is based on shuttle tankers equipped with pre-treatment plants. For offloading the ships are equipped with STL shipboard systems which can be connected to a STL buoy for injection to the wells. To allow for continuous injection to the wells, two STL buoys will be installed. This allows for connection of the arriving vessel before the departing vessel disconnects. The STL system is shown in Figure 56. For connection to the STL buoy a criterion of Hs 4.5 m is used. Estimates indicate the cost to be 18 €/t.

Study of ship size and logistics cases shows that a two ships solution is the preferred case. The main parameters of the tanks and the ship are presented in Table 32 and Table 33 below. A comparison between roundtrip times for a two, three and four ships logistics chain is shown in Figure 58.

Table 32 Tank parameters direct injection with two STL systems

No of tanks [-]	Length of tank [m]	Steel weight of tank including support [t]	Total volume in tanks [m^3]
6	40.4	621	32763

Table 33 Main dimension of ship for direct injection with two STL systems

Block coefficient [-]	Displacement [t]	Length between perpendiculars [m]	Breadth [m]	Draught [m]	Depth [m]
0.80	52088	181.8	35.1	10.2	18.0

A summary of the process plant is presented in chapter 11.4

Figure 58 Comparison between roundtrip times for a two, three and four ships logistics chain

11.4 Pre-treatment Plant

To be able to inject CO_2 at a pressure of 70 barg and a temperature of 0°C to the reservoir two solutions has been explored:

- Transport/storage at 7 barg and a pre-treatment plant to bring the CO_2 to 70 barg and 0°C
- Transport and storage at 70 barg and 20°C

The pre-treatment plant is skid mounted and consists of two trains each dimensioned for a capacity of 200 t/h CO_2. Each train consist of a booster pump pressurizing the CO_2 from 7 barg to 70 barg, a shell and tube heater, using seawater to heat the liquid CO_2 from -50°C to 0°C. The seawater system is a part of the ship systems.
The size of the skid is Length 15 m and width 5 m. The estimated total weight for the plant is 102 t.

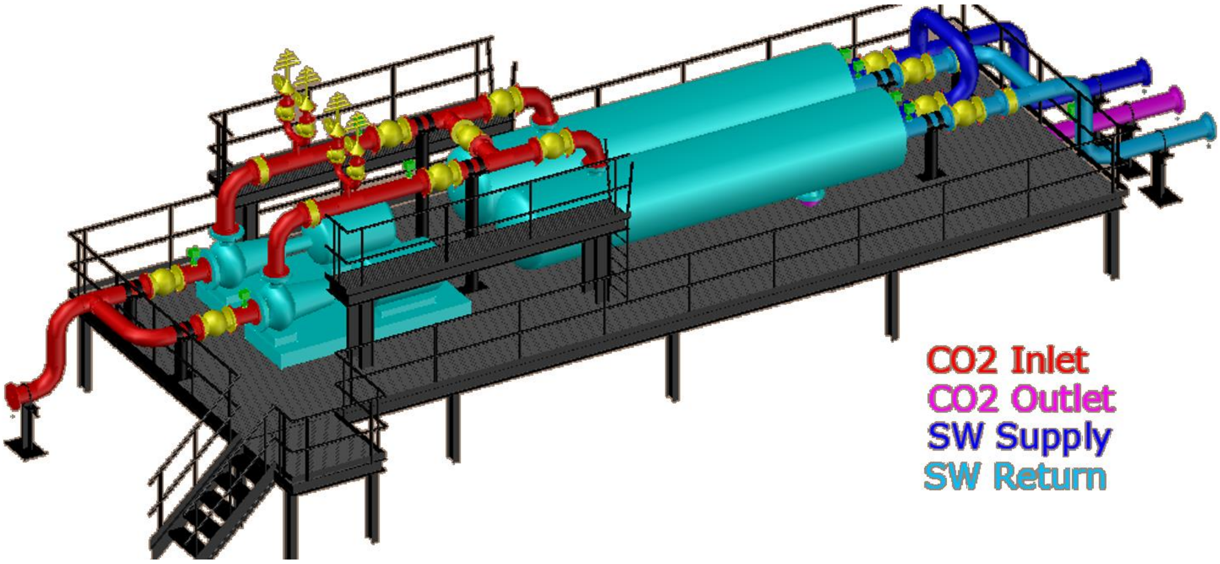


Figure 59 Pre-treatment plant

In the cases of direct injection there is no vapor return. This means that the energy needed for vaporizing CO_2 to fill the cargo tank during the offloading needs to come from the remaining liquid.

If energy has to be added to the liquid phase CO_2 in order to avoid pressure and temperature decrease during pumping, this can be done either by pumping a fraction of the contained liquid phase through heaters to vaporize liquid for gas return or by using electrical heating coils to maintain the temperature in the vessel.

A dynamic simulation, exploring this scenario is included in WP 6, ref (6), and the finding here is that the temperature drops by 3.9-4.1°C when unloading without vapor return.

12 WP 10 OFFSHORE UNLOADING - FURTHER STUDIES

12.1 Limiting parameters for ship connection

In WP4, ref. (12), three concepts of offshore unloading and injection of CO_2 has been explored, all assuming loading port Rotterdam and offloading in the North Sea (Gullfaks area), as described in the Design Basis, ref. (14):

Concept 1 - Ship Offshore Unloading with batchwise direct injection to well.
Concept 2 - Ship Offshore Unloading batchwise to FSI (Floating Storage and Injection unit).
Concept 3 – Ship Offshore Unloading by continuous direct injection.

The scope in WP10 has been to evaluate the limiting parameters for ship connection to mooring and offloading systems for future CO_2 tankers in the North Sea. It is considered that the systems for mooring and offloading CO_2 will be very parallel to the systems in use today for mooring and loading oil cargo in the North Sea. The challenge is that the CO_2 tankers may be smaller than the oil tankers, and thus that the current limiting parameters needs to be adjusted for the smaller ship sizes. Aframax oil tanker of typically 80 – 120 000 dwt has been used as refence since this is a quite normal ship size for offshore loading of oil cargo today. A small CO_2 tanker of 10 000 dwt has been used for evaluating CO_2 offloading. This ship size is far more flexible with respect to quay facilities at the capture site and will also require less intermediate storage at the capture site. It remains to be seen what the actual size in a future industry will be, however it will probably be in the interval between 10 000 and 100 000 dwt. FSI size will probably be larger than the CO_2 tanker size.

It is the Captain of the tanker who takes the decision on connection or not, mainly with regards to safety for the crew due to green sea on deck. The Captain's main decision criteria is the significant waveheight, Hs. This parameter is also referred to in the operation manuals for today's shuttle tankers. Other parameters such as wind speed and direction, current, roll motions etc are also important. These are further discussed in the report, ref (13).

Hs is forecasted by meteorologists and Hs is thereby applied for planning with regards to weather windows. During the operations, the Hs is predicted visually by the captain and it is also predicted by weather radars. Indicative Hs limiting values are listed in Table 34. Site specific calculations of the proposed ship design need to be done in cooperation with the mooring and offloading systems Vendor.

Table 34 Limiting parameters for connection

Concept	Limiting Hs (m)		DP		Offloading time 10 000 dwt
	Aframax 80 000 - 120 00 dwt	Ship 10 000 dwt	Required	Normally applied	
1	3.5 - 4.5	3.0	No	Yes	3 - 4 days
2	4.5	3.0	Yes	Yes	8 - 9 hours
3	4.5	3.5	Yes	Yes	3 - 4 days
Safety for the crew due to green sea on the deck is the main reason for the limitations for all the concepts					

The data has been acquired through contact with a mooring and offloading system Vendor, with ship Operators and through studies of operating manuals for tandem offloading.

12.2 Parametric study of transport volumes

Relevant logistics cases with corresponding cost for the three concepts listed in chapter 12.1 has been developed in WP4, ref. (12). This calculation assumed two injection wells as stated in the Design Basis, ref. (14).

The scope in WP10 has been to stepwise increase the transported volumes of CO_2 and develop the logistics cases including ships and FSI size and cost for the three concepts. Finally, a cost comparison between the cases is done. The concepts were calculated with two injection wells in WP4, each with a theoretical capacity of 1.0 Mt/y. By increasing the number of wells to respectively four and six, higher volume cases are explored. The work done is not to a level where it can be claimed that the optimal solution for each case has been identified. It is however considered sufficient to conclude on any cost trends related to increasing the number of wells and corresponding volumes of CO_2. Note that the cost calculation includes cost of Ships, FSI, mooring and transfer systems such as STL, BLS etc but not the wells, nor any land based facilities. A depreciation time of 20 years is assumed.

The result of the cost calculations is summarized in Figure 60. A clear trend towards reduced cost when increasing volume can be seen for all concepts, with the largest reductions identified on Concept 2 with the FSI. The single most important reason for the cost reductions is the elements connected to the offshore unloading, mooring and injection operations. Typically cost of SAL, STL and FSI systems will not necessarily increase linearly with the transported amount of CO_2. The logistic chains for the lower volumes may have a surplus capacity which can be utilized in the higher volume cases without adding more units.

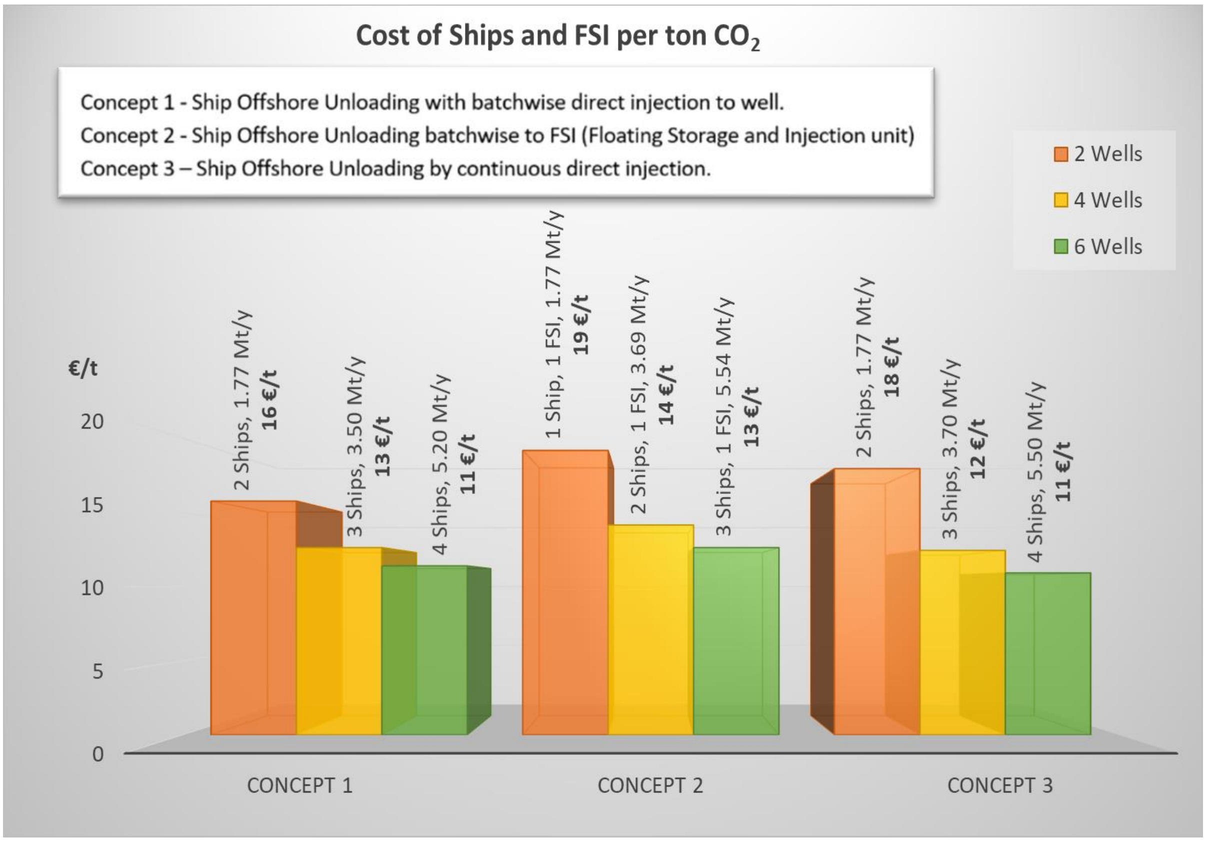


Figure 60 Cost of Ships and FSI per tonnes CO_2 (including mooring and transfer systems)

13 WP 5 LOGISTICS GHG IMPACT

13.1 General

When Carbon Capture and Storage (CCS) is implemented in large industrial scale, the capture and the storage will normally not be at the same location. More likely a typical scenario will be similar to the base case of the CO2LOS II project with capture from land-based emitters and storage in offshore locations. The logistics needed for such a CCS chain has been studied. Ship transport of liquefied CO_2 is a key part of the base case CCS chain. Because of that, liquefaction of the captured CO_2 must be considered. The overall target of CCS is to reduce the GHG footprint.

However, CCS chain of operation itself emits CO_2, either through loss of captured CO_2 in the process or through consumption of electricity and fuel. Therefore, it is important to investigate quantitatively the possible GHG emissions within the whole CCS process itself. The current study separates the associated processes of the CCS chain within the CO2LOS II project scope and then calculates the GHG emissions separately for each item based on theoretical calculations and mathematical modelling. This associated GHG emission is expected to be significantly lower than the quantities of CO_2 stored, still it is worthwhile to estimate. All the processes in the transport chain are split into five main process areas:

- Liquefaction
- Intermediate storage
- Pumping/loading/unloading
- Ship transportation
- Containment boil-off

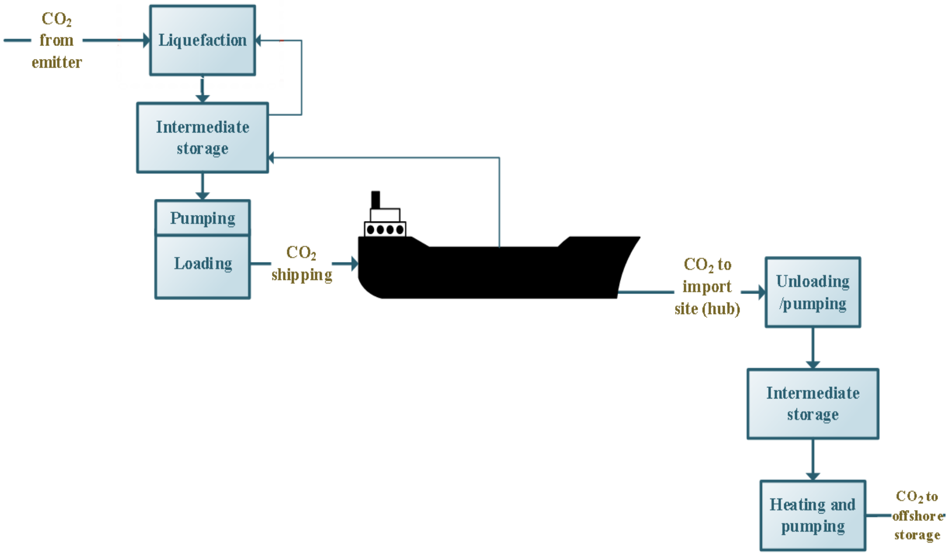


Figure 61: Scope of the GHG emission investigation

An investigation of emission mitigation cost is executed. The investigation has shown that the boil-off is not a major contributor to the emissions in the transport chain. The effort should be used to reduce the fuel or power consumption or to change the fuel type to a lower carbon intensive fuel or power mix.

The main emissions come from running the liquefaction plant. This is due to the electricity consumed for liquefaction, and compression in particular. From the ships the main CO_2 emission comes from the diesel engine. Change to another fuel may give a reduction of emission and thereby the emission cost. On the other hand, the cost of the emission is relatively low compared to volumes transported in the chain. It is a great benefit to re-liquefy the boil-off gas from the intermediate storage instead of releasing it to the atmosphere.

For this base case, 3.8 % of the transported CO_2 is emitted either as direct emission or emission from power consumption during the transport of the CO_2. If the emissions from the liquefaction plant was not to be included, less than 1 % of the transported volume is emitted.

Table 35 gives an overview of the emissions and cost for each process area, further details in ref (1):

Table 35 Summary of GHG impact from base case operation and related cost, ref (1)

Process	GHG emission	Event related cost k€/y
Liquefaction		
Electricity consumption	55 kt/yr (8300 hr/yr)	1375
Intermediate storages		
Electricity due to re-liquefaction of BOG	5.8 kg/hr (8300hr/yr)	1.2
Pumping/loading/unloading		
- Loading	2624.5 kg/loading	13
- Unloading	3201.9 kg/unloading	16
Ship operation (3 ships)		
- CO_2 from main engine exhaust	$19.25\ \mathrm{t_{CO_2}/day_{(per\ ship)}}$	404
- CO from main engine exhaust	$0.02\ \mathrm{t_{CO}/day_{(per\ ship)}}$	-
- NOx from main engine exhaust, needs to be tier III compliant	$0.12\ \mathrm{t_{NO_X}/day_{(per\ ship)}}$	120
- CO_2 from fugitive emissions from the cargo system	$0.02\ \mathrm{t_{CO_2}/day_{(per\ ship)}}$	3
Containment boil-off		
- Ship cargo tanks	$0\ \mathrm{t_{CO_2}/day}$	–
- Onshore storage tank	$3.39\ \mathrm{t_{CO_2}/day}$	55

For the calculation of emissions from electricity production, a factor of 0.267 kg_{CO2}/kWh is applied. A sensitivity calculation for lower factors is calculated in the report, presented significantly lower emissions from electricity consumption.

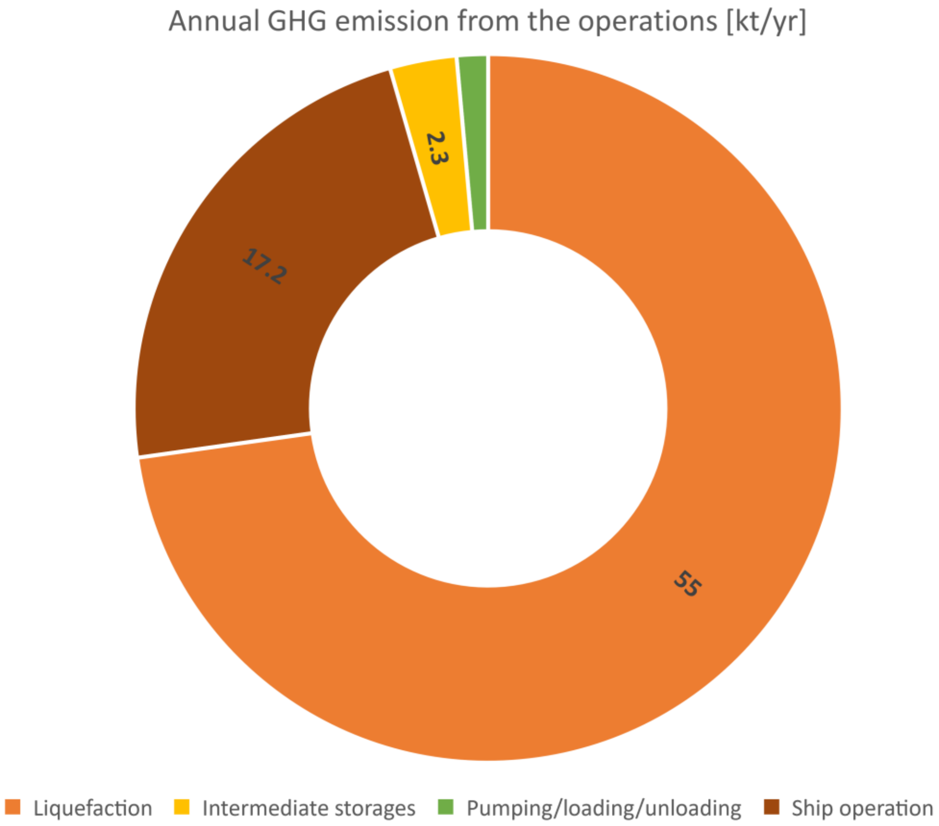


Figure 62 Annual GHG emission from the operations

13.2 Boil off calculations

Liquefied CO_2 is continuously vaporized (depending on the actual heat leak from surroundings), and the pressure is increasing inside the containment over time. It may result in dangerous over pressurization. However, PSV's are installed to handle this event. To avoid release of CO_2 to the atmosphere, the vaporized gas is released as BOG during the transportation and storage. For both economic and environmental reasons, it is important to design the containments to minimize the BOG. However, these storage tanks are not 100% heat protected and consequently some heat will leak into the containment over the time. Adding more heat in to liquefied CO_2 at equilibrium will increase the temperature as well as the pressure in the system due to further vaporization of liquefied CO_2. To prevent any danger of over pressurization, the vaporized gas is released as BOG. Because of that it is important to make a good estimation of the amount of possible BOG.

The main parameters that dictate the behaviour of CO_2 BOG, are the temperature difference between cargo and ambient temperature and the insulation thickness.

13.2.1 Results and the conclusion

A summary of the results from the calculation can be seen in the Table 36 . The cargo ships and FSI gives a duration of 46 days without release of BOG. This means that heat leak is transferred to pressure increase in the storage tank during the first 46 days and after that pressure increase will be reached to the maximum design pressure of the storage tank and the BOG must be released. However, this creates a more than enough time frame for ship and FSI to complete their operations. there is no need of further attention on risk of GHG emission due to BOG under the base case operations.

Table 36 Overview of the results

	Loading pressure	Set point for pressure release valves	Possibility for pressure accumulation	Heat flow into a single tank	N_{days}	n_T	$(\dot{m}_{BOG})_{Total}$ Per containment
Onshore storage	6 barg	$7^{\#}$ barg	No	13.4 kW	0	2	$3.39\ t_{CO_2}/day$
Cargo ship	6 barg	7 barg	Yes	11.8 kW	46	2	0^{**}

[#] Even though the design pressure for the cargo tank is 7 barg, the maximum operational pressure is only 6 barg as the intermediate storage should maintain at 6 barg pressure since the loading pressure is 6 barg.
** BOG will start if the liquefied CO_2 is stored in each containment more than 46 days.

However, the modelling work revealed that the tanks used for the onshore intermediate storage need further attention, since there is no possibility for pressure control based on pressure accumulation. Because of that BOG is produced all the time. Even though there is a possibility to send the BOG back to the liquefaction plant, it affects the efficiency of the whole operation. Some changes to minimize the BOG would optimize the process. Current modelling work predicted that, changing the insulation material type from Polyurethane foam to Aerogel may benefit a reduction of 38% BOG flow rate. Further, the model predicts 58% reduction of BOG if 30 cm thick layer of Aerogel is used as the insulation and that is a reduction of, around $2\ \mathrm{t_{CO_2}/day}$.

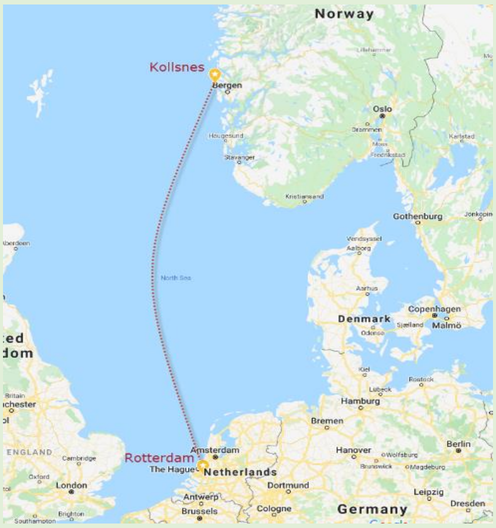
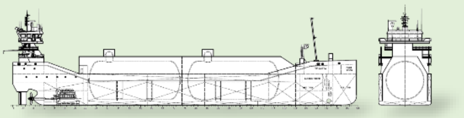
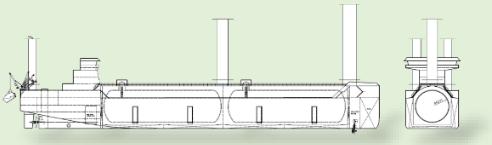
PART III – CCS CASES WITH COST

Costs are based on cost calculations in the work packages. Battery limits for the CO2LOS II project are the boundaries for the cost examples. The final numbers are presented as accumulated cost after 20 years of operation. No cost/tax for GHG emissions is included, however this may prove to be an important cost element in the future.

1 THE NORTH SEA BASE CASE

Cost calculation of the North Sea base case is done for ship concepts A (conversion) and B (newbuild). Concept C (autonomy) is not found relevant due to the low TRL level. In Table 37 the basis for the cost calculations is listed.

Table 37 Basis for cost calculations on the North Sea trade applicable for concepts A and B

Basis for cost calculations on the North Sea trade		
	Export port (with a quay facility)	Rotterdam
	Import port (Northern Lights facility)	Kollsnes
	Distance one way, appx	540 nmi
	Transport Volume	2.0 Mt/y
	Transport Pressure (operating)	6.0 barg
	Liquefaction on land	
	Intermediate storage on land in vertical tanks	
	Intermediate storage capacity (1 x ship)	varies
	Loading Arms on export terminal facility	
	No onboard CCS and no return cargo	
Concept A – 4 ships 	Concept B – 3 ships 	

1.1 Concept A and Concept B, 20 years

Summary of costs for the North Sea case after 20 years operation with respectively Concept A and Concept B is given in Figure 63. Cost of delivering to import terminal at Kollsnes is not included.

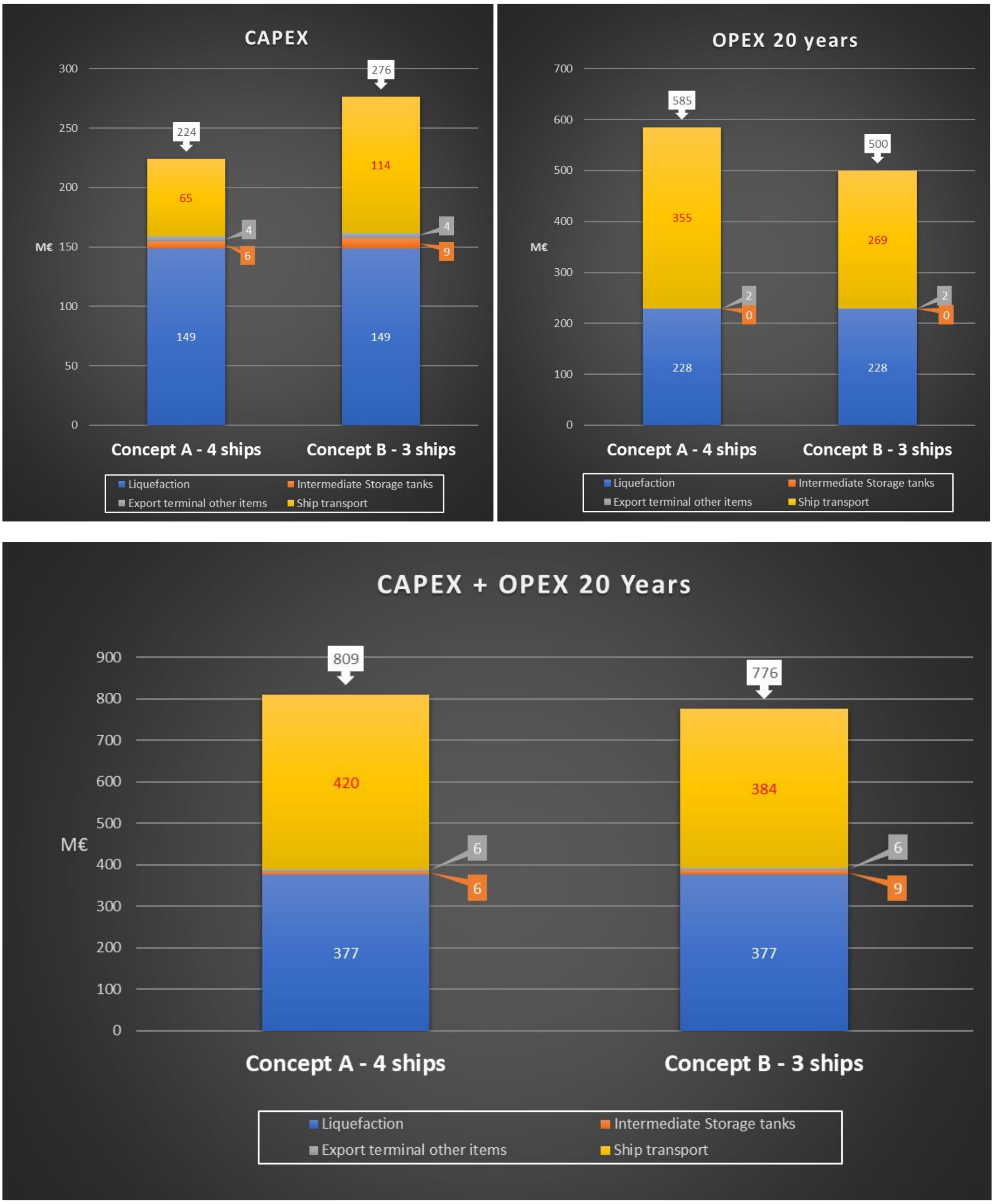


Figure 63 CAPEX + 20 years OPEX for North Sea case Concept A and Concept B, delivery cost to import terminal not included

1.2 Concept A and Concept B

Shorter depreciation periods of respectively 5 and 10 years is calculated for the two concepts, results are given in Figure 64 and Figure 65.

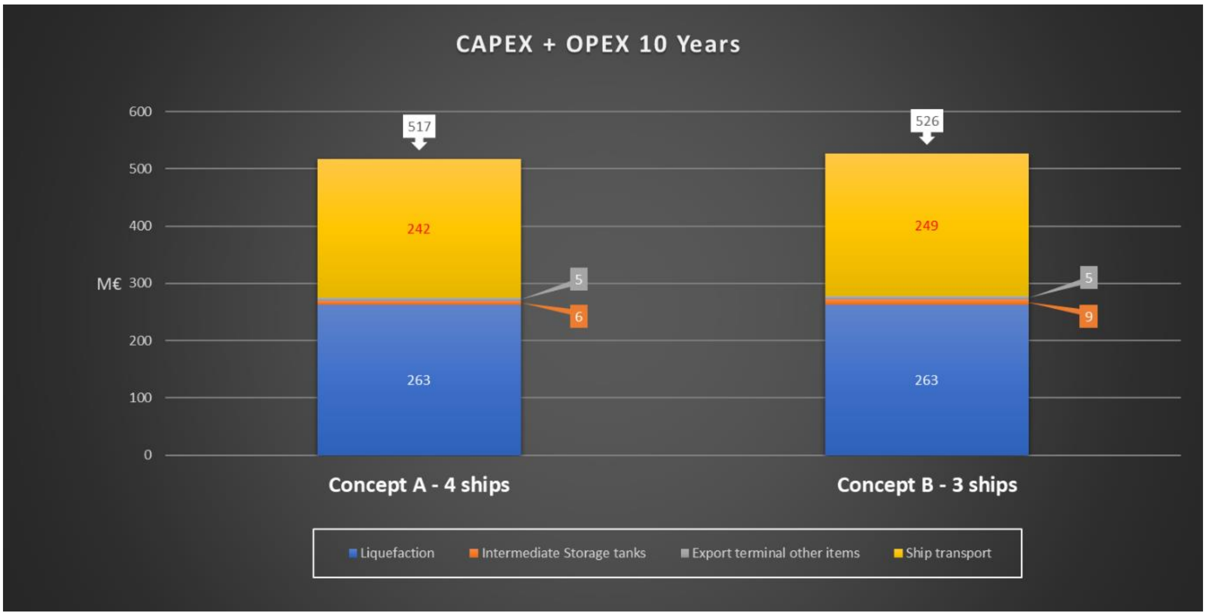


Figure 64 CAPEX + 10 years OPEX for North Sea case Concept A and Concept B, delivery cost to import terminal not included

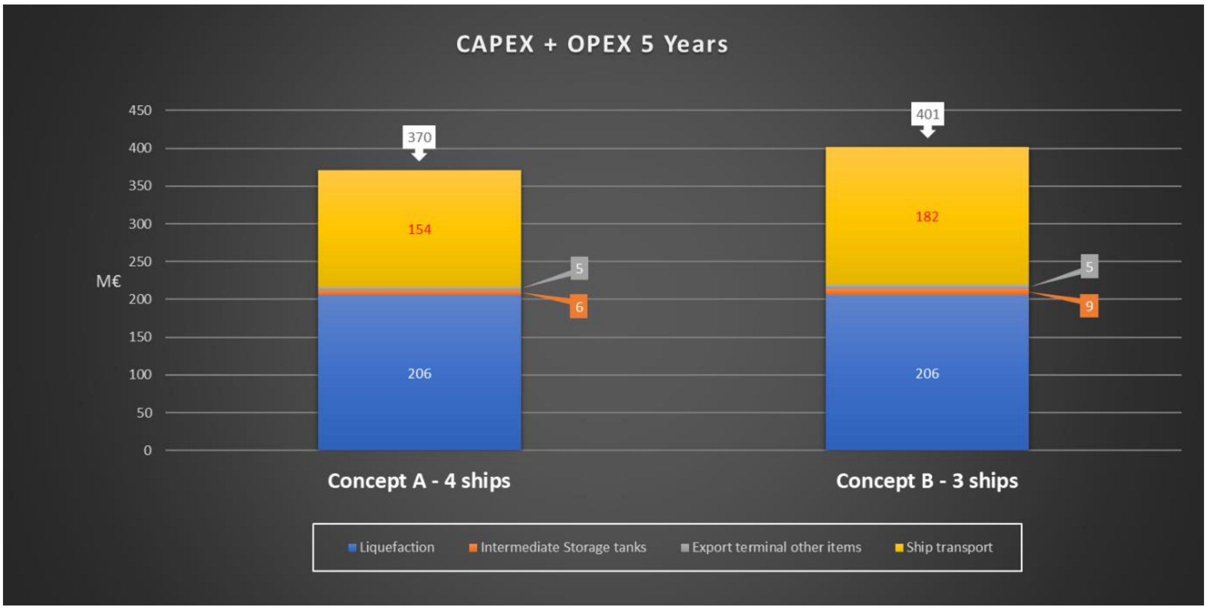


Figure 65 CAPEX + 5 years OPEX for North Sea case Concept A and Concept B, delivery cost to import terminal not included

The conversion concept A is the best alternative for short depreciation periods while Concept B is the preferred solution for the 20 years base case, ref Figure 66.

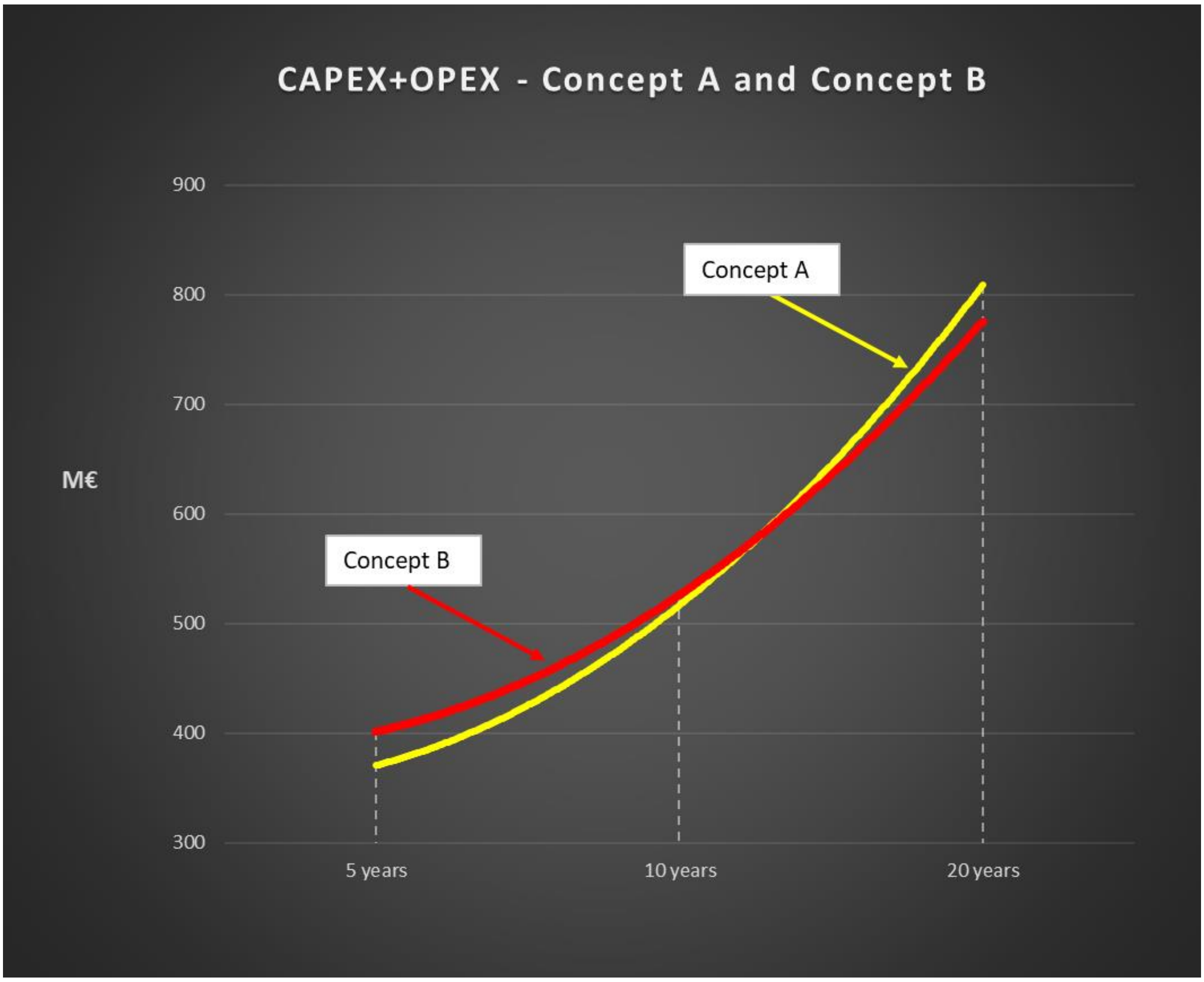
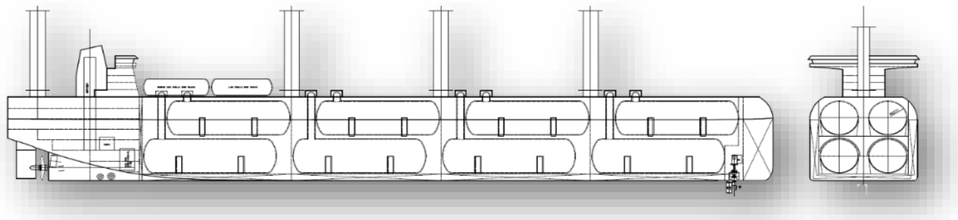


Figure 66 CAPEX + OPEX development

2 THE TRANS-ATLANTIC CASE

Cost calculation of the trans-Atlantic case is done for ship concept D. In Table 38 the basis for the cost calculations is listed.

Table 38 Basis for cost calculations on the Trans-Atlantic case, applicable for Ship Concept D

Basis for cost calculations on the Trans-Atlantic trade		
	Export port (with a quay facility)	Rotterdam
	Import port	Port Arthur
	Distance one way, appx	5000 nmi
	Transport Volume	3.0 Mt/y
	Transport Pressure (operating)	6.0 barg
	Liquefaction on land	
	Intermediate storage on land in vertical tanks (4000 m^3 each)	
	Intermediate storage capacity (1 x ship)	77 500 m^3
	Loading Arms on export terminal facility	
	Onboard CCS	
	No return cargo	
Concept D - 4 ships 		

2.1 Concept D, 20 years

Summary of costs for the trans-Atlantic case after 20 years operation is given in Figure 63. Cost of delivering to import terminal is not included.

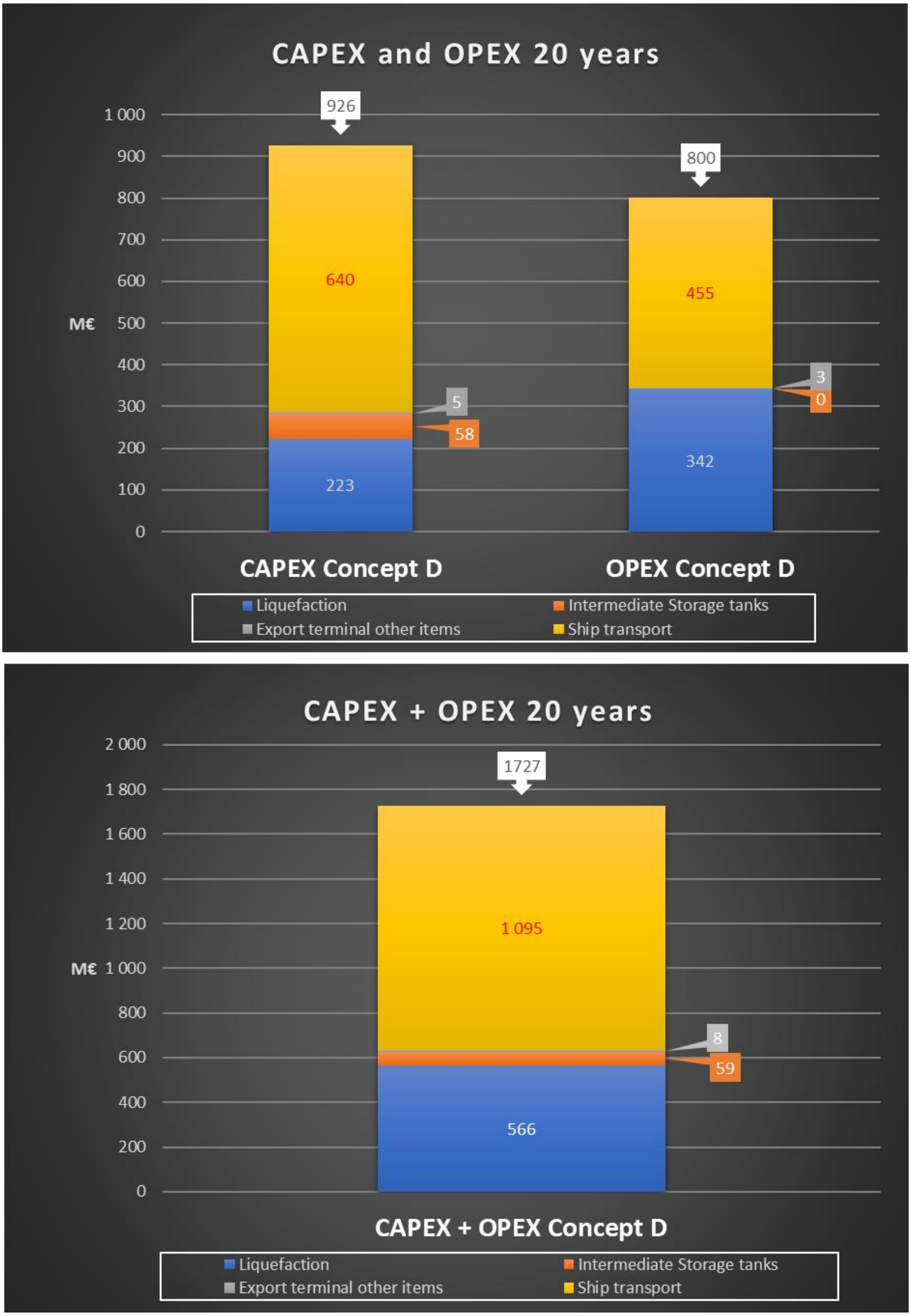
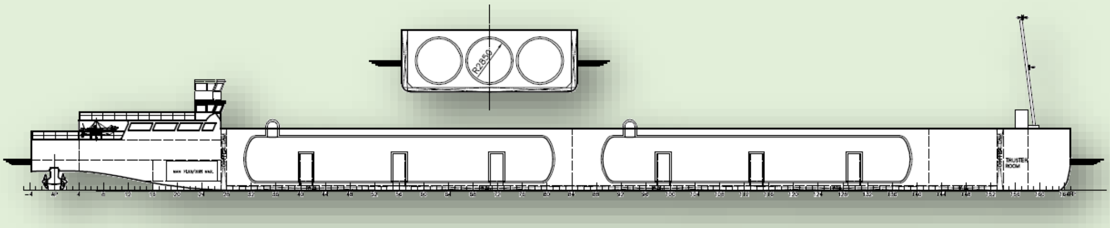


Figure 67 CAPEX and OPEX for trans-Atlantic case with Concept D, delivery cost not included

3 THE INLAND AND ESTUARY CASE

Cost calculation of the inland and estuary case case is done for ship concept E. In Table 39 the basis for the cost calculations is listed.

Table 39 Basis for cost calculations on the inland and estuary case applicable for Ship Concept E

<table>
<tr><th colspan="3">Basis for cost calculations on the inland and estuary trade</th></tr>
<tr><td rowspan="11">
</td><td>Export port (with a quay facility)</td><td>Inland</td></tr>
<tr><td>Import port</td><td>Coastal hub</td></tr>
<tr><td>Distance not defined, 218 roundtrips per ship assumed</td><td></td></tr>
<tr><td>Transport Volume</td><td>2.0 Mt/y</td></tr>
<tr><td>Transport Pressure (operating)</td><td>6.0 barg</td></tr>
<tr><td>Liquefaction on land</td><td></td></tr>
<tr><td>Intermediate storage on land in vertical tanks (4000 m^3 each)</td><td></td></tr>
<tr><td>Intermediate storage capacity (1 x ship)</td><td>6 000 m^3</td></tr>
<tr><td>Loading Arms on export terminal facility</td><td></td></tr>
<tr><td>No onboard CCS or return cargo</td><td></td></tr>
<tr><td colspan="2"></td></tr>
<tr><td colspan="3">Concept E – 4 ships
</td></tr>
</table>

3.1 Concept D, 20 years

Summary of costs for the inland and estuary case after 20 years operation is given in Figure 63. Cost of delivering to import terminal is not included.

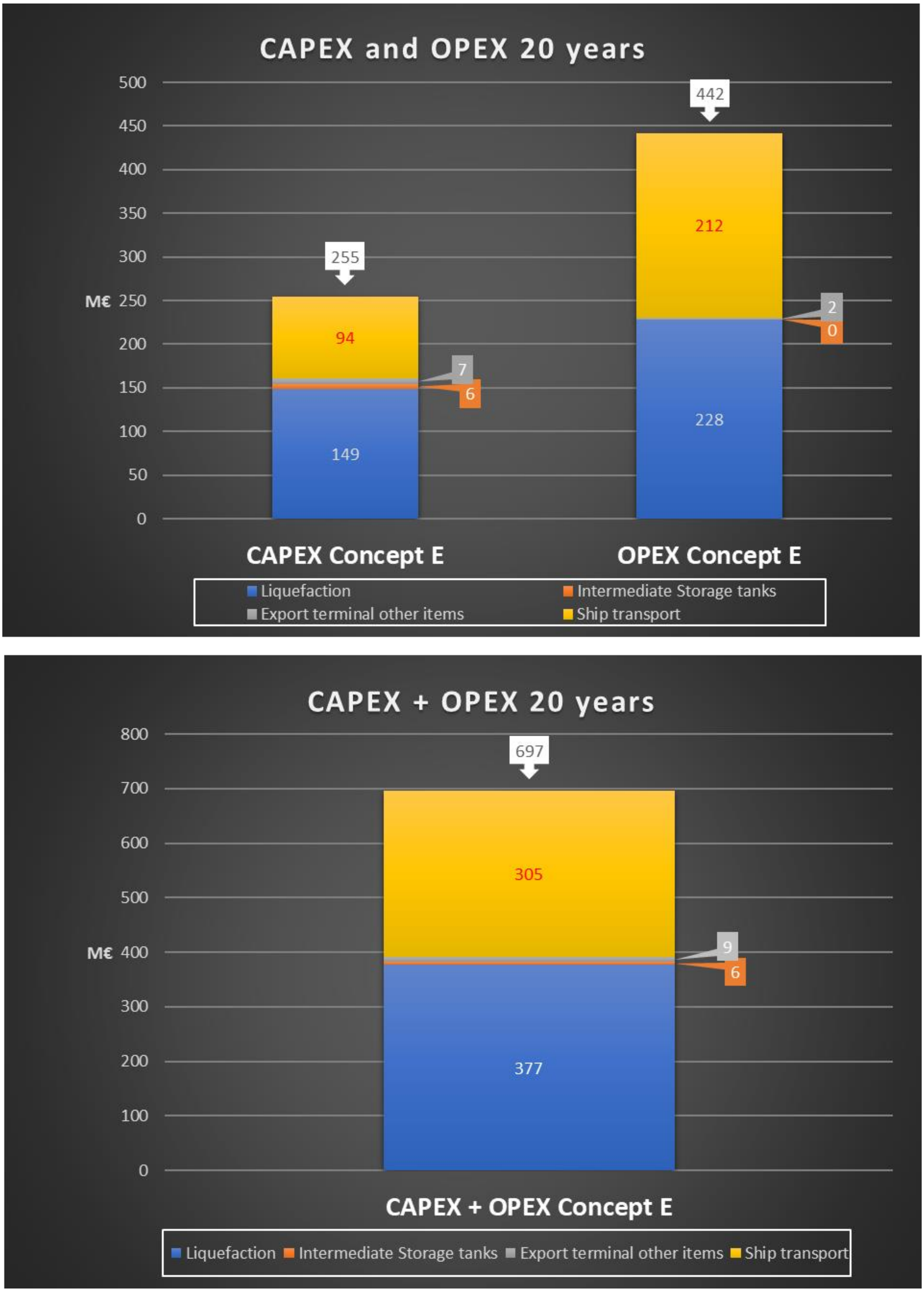


Figure 68 CAPEX and OPEX for the inland and estuary case with Concept E, delivery cost not included

PART IV – ABOUT THE PROJECT

1 BACKGROUND FOR CCS

1.1 Carbon Capture and Storage

Carbon Capture and Storage is addressed by IEA as one of the key technologies of reaching the Paris agreement 2°C goal. In the IEA 2°C scenario 1 gigatonnes/y CO_2 will need to be captured by 2030 ramping up to 5 gigatonnes/y in 2045. This will require huge logistic operations. CCS/CCU transport has up to now been based on pipelines. Transport of CO_2 by ship represents an alternative when pipelines are too expensive due to distance, volume, and depreciation period. Food grade CO_2 has been transported with ships for decades, but these volumes are rather small compared to the planned CCS projects.

1.2 The CO2LOS II project

The scope of the CO2LOS II (CO_2 Logistics by Ship Phase II) project is to reduce the cost of CO_2 ship transportation by utilizing new technology and investigate optimization possibilities in the logistic chain. The final report will serve as a toolbox with different solutions and as an estimate of when these solutions may be applicable for CO_2 transport. The CO2LOS II project will not involve development of new technology, only bundling of existing technologies. CO2LOS II also wants to explore what will be the next steps in developing shipping operations for CO_2.

CO2LOS II

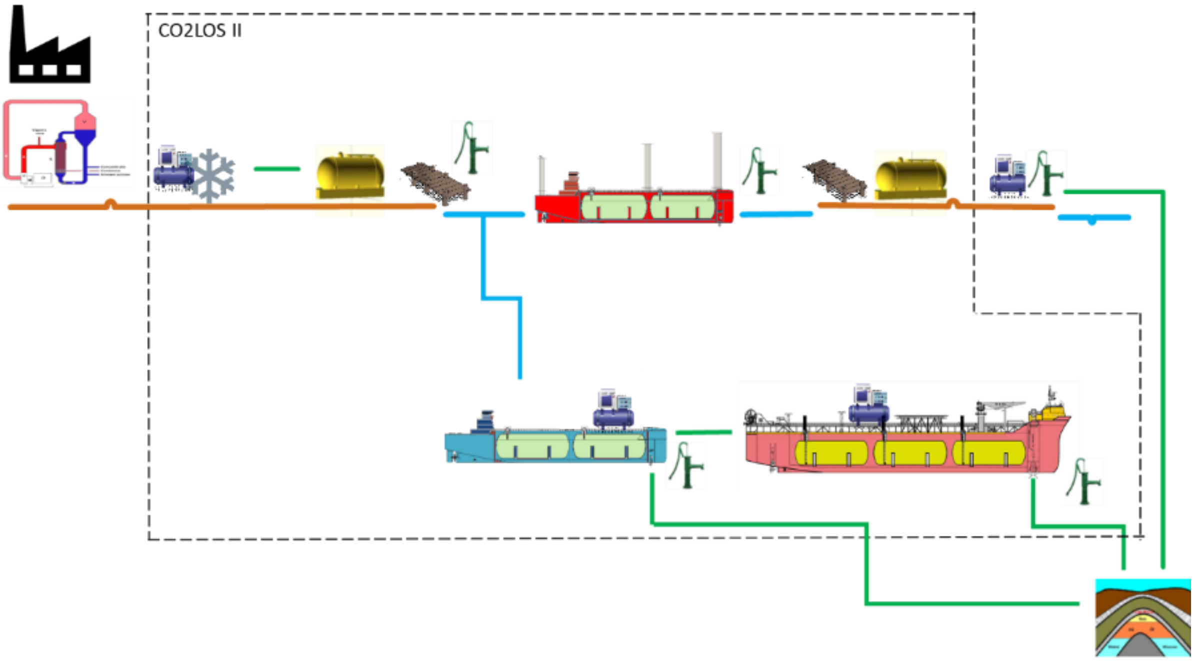


Figure 69 CO_2 logistics case

1.2.1 The CO2LOS II project in relation to other projects

In Figure 70 the relationship between the CO2LOS II project and other relevant project is visualized. Discussions started in April 2018 between Brevik and SINTEF together with the industrial partners Total, Shell, Equinor and Gassco, how to cut the cost of CO_2 logistics. This resulted in the birth of the CO2LOS chain of projects. In the pre-study CO2LOS I issued by the end of 2018, present knowledge was consolidated, and potential cost drivers identified. In CO2LOS I a method statement was developed, describing the objectives and scope of the CO2LOS II project. A later project CO2LOS III is currently being planned. Benchmarking towards other CCS projects is constantly ongoing.

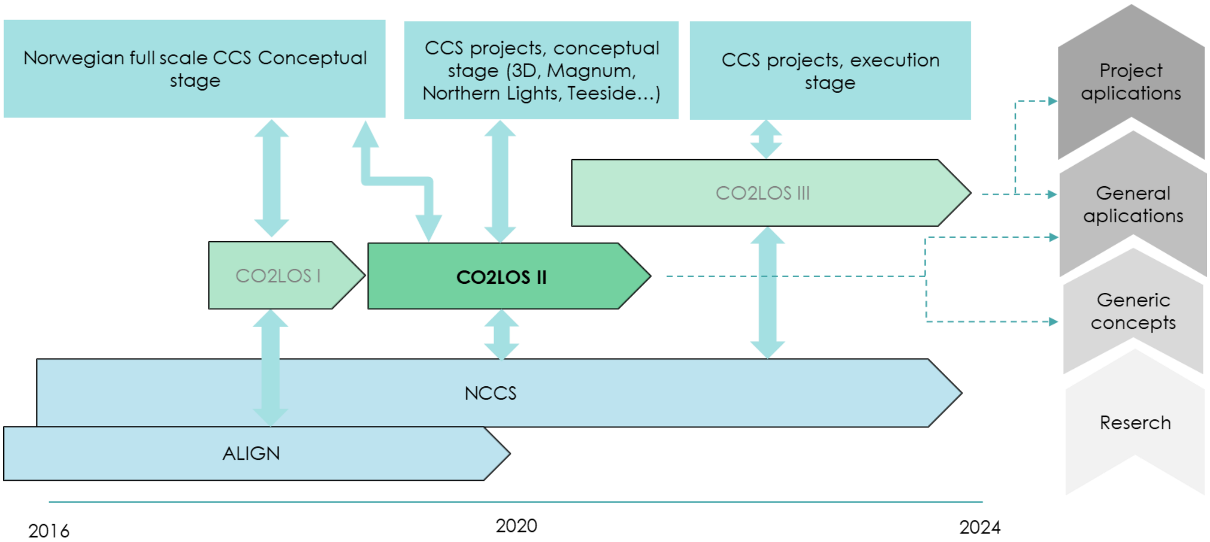


Figure 70 CO2LOS II related to other projects

2 CO2LOS II - PROJECT EXECUTION AND ORGANIZATION

2.1 Project execution

The project started up in May 2019 as a consortium of 7 partners. BP joined as a partner in the spring of 2020. The project had an initial finish date by end of October 2020. The scope was extended when BP joined the project and the completion date postponed one month to the end of November 2020. The first project documents were issued in late August 2019, since then WP reports covering the different topics of the CO2LOS II project, has been released according to plan.

2.2 Project organization

The project organization has been formalised through a consortium agreement between the partners. Funding is made by the partners and by CLIMIT through Gassnova. Brevik Engineering AS is the formal project owner and such the responsible body related to the project deliveries to Gassnova.

During the project, contact has been made with suppliers of relevant technologies, governing bodies, and operators within relevant segments of the industry.

SINTEF and Brevik Engineering AS were assigned with the main bulk of the project budget and have been responsible for reporting and administration activities. The other partners have contributed with know-how, industry contacts, input during project meetings and review of all project documents. The organization is shown in Figure 71.

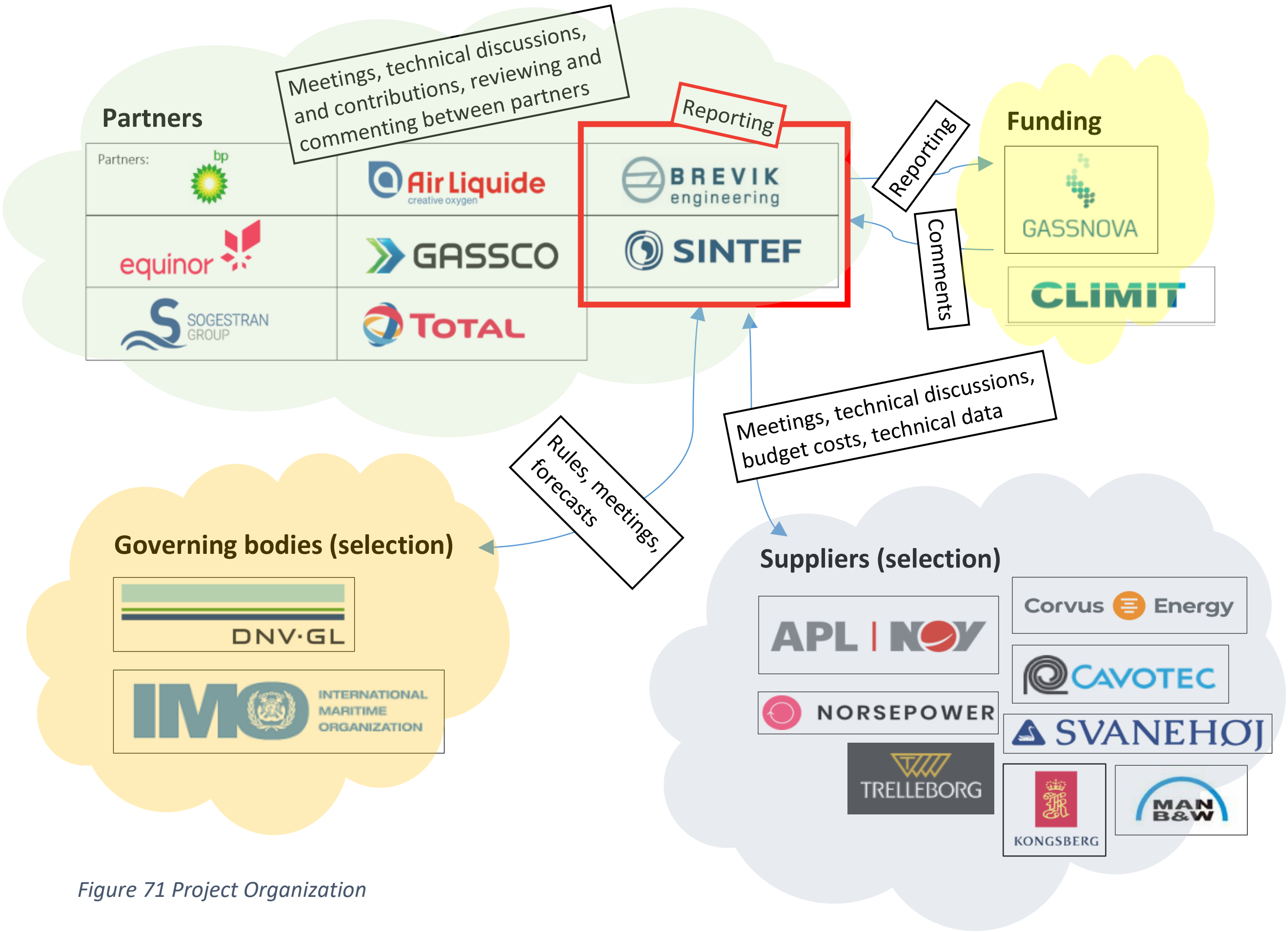


Figure 71 Project Organization

3 DOCUMENT HISTORY

Revision	Date	Reason for Change
A	2020-11-06	Issued for DC
01	2020-11-18	Issued for Partner comments
02	2020-12-04	Updated with Partner comments
03	2020-12-16	Prepared for public publishing, detailed cost data omitted

4 PURPOSE AND SCOPE

4.1 Purpose

The CO2LOS II project is documented in detail through 13 work package reports. In addition, the final report (this report) is issued for the purpose of summarizing the project and providing a tool to be used for accessing the project information.

4.2 Scope

The final report serves as a toolbox for CCS logistics by ship, containing a summary of various engineered conceptual technical solutions with associated costs and estimate of when these solutions may be applicable for CO_2 transport.

4.3 Method

The technical solutions will have to be adjusted when a firm CCS project is developed with decisions of volumes, export and import site, transport pressure, location, and characteristics of the reservoir, etc. Acknowledging this, the methodology used for development of the solutions, including logistics, simulations, calculations, analysis, results from discussion with partners and vendors and literature studies are an important part of the toolbox. These tools are in general not available in the final report but are documented in the separate work package reports. In order to utilise the full benefit of the toolbox, the reader will have to visit the separate work package report of interest.

5 ABBREVIATIONS

API	American Petroleum Institute
ARA	Amsterdam, Rotterdam, Antwerp
BLS	Bow Loading System
BOG	Boil Off Gas
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CPI	Cost Performance Index
CS	Carbon Steel
DCS	Data Collection System
DP	Dynamic Positioning
DWT	Deadweight tonnes
EEDI	Energy Efficiency Design Index
ESA	European Space Agency
ETS	Emission Trading Scheme
EU	European Union
EUR	Euro
FE	Finite Element
FSI	Floating Storage and Injection
GHG	Green House Gases
HAZID	HAZard IDentification
IEA	International Energy Agency
IGC	International Gas Carrier
IMO	International Maritime Organization
KO	Knock Out
LEG	Liquefied Ethylene Gas
LNG	Liquid Natural Gas
LP	Low Pressure
LPG	Liquefied Petroleum Gas
MARVS	Maximum Allowable Relief Valve Setting
MEA	Mono Ethanol Amine
MEL	Main Equipment List
MP	Medium Pressure
MPa	Mega Pascal
MRV	Monitoring, reporting and verification
NASA	National Aeronautics and Space Administration
NCCS	Norwegian CCS research Centre
NCS	Norwegian Continental Shelf
NECA	NOx Emission Control Areas
nmi	nautical miles
NOK	Norwegian Kroner
NOx	Nitrous Oxides
NPD	Norwegian Petroleum Directorate

OD	Outer Diameter
ppmv	parts per million volume
PSV	Pressure Safety Valve
SAL	Single Anchor Loading
SECA	SOx Emission Control Areas
SEEMP	Ship Energy Efficiency Management Plan
SFI	Skipsteknisk Forsknings Institutt
SOx	Sulphur Oxides
SS	Stainless Steel
STL	Submerged Turret Loading
SWL	Safe Working Load
TBD	To Be Decided
TRL	Technological Readiness Level
USD	United States Dollar
WHRU	Waste Heat Recovery Unit
WP	Work Package

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5. —. *19204-Z-RA-100-008 WP 11 Floating Liquefaction facility.*

6. —. *19204-Z-RA-904-001 WP 6 Low Pressure Design.*

7. —. *19204-Z-RA-904-004 WP 8 Ship Tanks beyond prescriptive Class Rules.*

8. —. *19204-Z-RA-100-003 WP 2 Ship Technology.*

9. —. *19204-Z-RA-100-009 WP 12 Carbon Limits database.*

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11. —. *19204-Z-RA-100-005 WP 9 Multipurpose use of Ships.*

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