Report Classification: Public

Project:

CO2LOS
CO2 Logistics by Ship Phase III

Document Title:

CO2LOS III - Final Report

Partners:		
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Project co-sponsor:

CLIMIT

03	2023-05-03	Issued for Public Use	GN	KHK	RS
02	2023-04-18	Public Report Issued for Partner Comments	GN	KHK	RS
01	2023-04-13	Issued for Partners	GN	KHK	RS
Revision	Date	Reason for Issue	Prepared	Checked	Approved
Document Number:		21206-Z-RA-100-010		Revision:	03

1 Contents

SUMMARY

The scope of the CO2LOS III (CO2 Logistics by Ship Phase III) project is to further increase the knowledge base for future ship based CCS projects. The Project started 1st of December 2021 with a duration of approximately 1.5 years. The project consists of seven work packages (WPs) related to CCS logistics by use of ships. Summaries from each WP follow below. The WPs are further described within this report. This public report is a condensed issue of the complete project reports which are available to the project partners.

WP1 – Cost Estimation Tool for CCS Scenarios

A CCS logistics cost calculation tool is the delivery from this WP, together with a User Manual, a Design Basis and a brief description of the Software Architecture.

The target was to develop a cost tool for different CO_2 transport scenarios as a part of a CCS chain. The philosophy was to generate bottom-up engineering models with associated CAPEX and OPEX cost figures based on a minimum of required user inputs but with extensive possibilities for refinement of default input values.

The model was to include all relevant steps between but not including, capture and storage. Both pipeline, ship and combinations of these have been covered. One of the main purposes of the tool is to enable comparison of pipeline and ship transport costs. The main input and cost presentation page is shown in Figure 1. The model covers multi step logistic chains up to three steps (ship-pipeline-ship or other combinations). The results are presented as high level unclassified cost estimates. The tool is available for use to all Project partners but the property rights to the program lies with Brevik Engineering and SINTEF. The program itself is not publicly available.

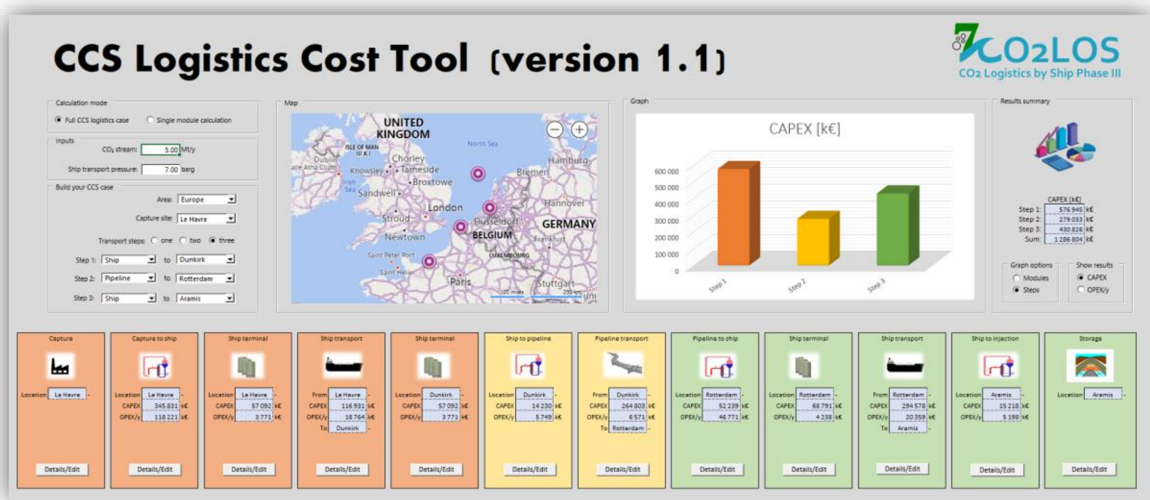


Figure 1 CCS Logistics Cost Tool - Frontpage

WP2 - Tank Arrangement for Large CO_2 Carriers

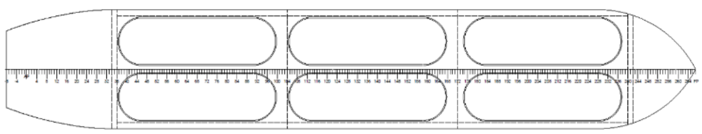
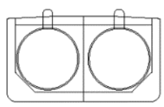
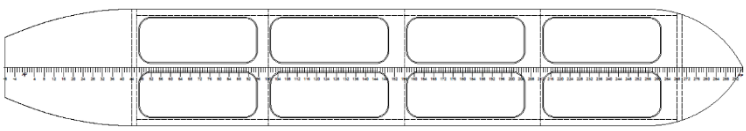
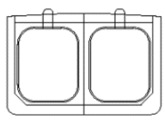
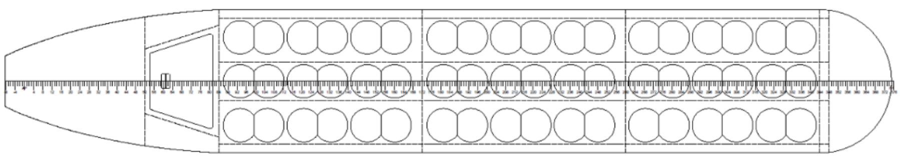
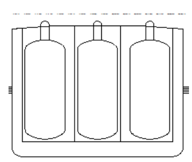
The aim of the work package is to optimize ship designs for the carriage of large quantities of CO_2 over long distances, with low emission ships.

In order to optimize the tank size, it was necessary to decide on a favourable pressure for the transport of large ship loads of CO_2. It is preliminary concluded with an optimal mechanical design pressure of 8.5 barg and a corresponding maximum operational pressure of 7 barg applicable for large ship carriers of CO_2. This reflects the desire to go closer to the triple point to reduce tank weight and increase the volume that can be handled on each trip, and at the same time considering the safety issues when operating close to the triple point. The optimal pressure may however vary with changes in the key drivers.

Based on the selected pressure, two suitable materials (NV 4-4L and NV 5Ni/a) and various tank shapes - a portfolio of tanks are calculated and sized to the max possible sizes. These tanks are used as a basis when arranging the ship cargo blocks for various ship sizes.

3 sizes of ship are presented: 50 000 t, 80 000 t, and 150 000 t cargo capacity. The purpose was to determine if there is an optimal size in general, for large CO_2 carriers, and to show that the different sizes have different optimal tank arrangements. Based on an evaluation the preferred arrangements are selected as shown in Table 1. Beam, length and draught restrictions i.e. due to harbour limitations has not been applied as these are case specific parameters.

Table 1 Tank arrangement summary

Cargo Capacity	Tank description Tank material	Vessel size	No of tanks Dimension
50 000 t	Horizontal Cylindrical NV 5Ni/a	220.0 m x 37.8 m	6 D = 14.8 m, L = 50 m
			
80 000 t	Prismatic NV 4-4L	242.4 m x 38.1 m	8 L = 38.5 m, B = 14.5 m, H = 18.0 m
			
150 000 t	Vertical Bilobe NV 4-4L	306.8.0 m x 49.6 m	27 D = 11.6 m, H = 28.0 m
			

WP3 – Floating CO_2 Terminals

The concept of a floating terminal should be considered as an alternative to a land-based terminal for CO_2 export or import. Floating terminals may include different functions and levels of complexity and the size may be different. This report describes a modular terminal system which can facilitate different requirements. A description of major and minor functions and options for such a terminal is included.

The design will be modular, but the building of the floating terminal with the storage systems will be done as a complete unit at a shipyard. The process modules such as the liquefaction system, if installed, will preferably be skid mounted on the deck of the terminal. The possibilities and variations are many. In this WP, as an example, two possible configurations A and B have been established. For both cases the CO_2 will be stored at 6.5 barg and -47°C.

The terminal Case A specification is mimicking the functions and design basis of the Stella Maris CCS Project ref. (1) and is able to receive tanker sizes up to 50 000 m^3 of liquid CO_2, ref. Figure 2.

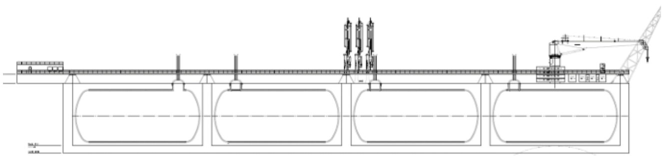


Figure 2 Case A

The terminal Case B specification is a larger fictitious case located in a remote area and being able to receive tanker sizes up to 150 000 m^3 of liquid CO_2 and with a terminal storage size of 180 000 m^3 liquid CO_2, ref. Figure 3.

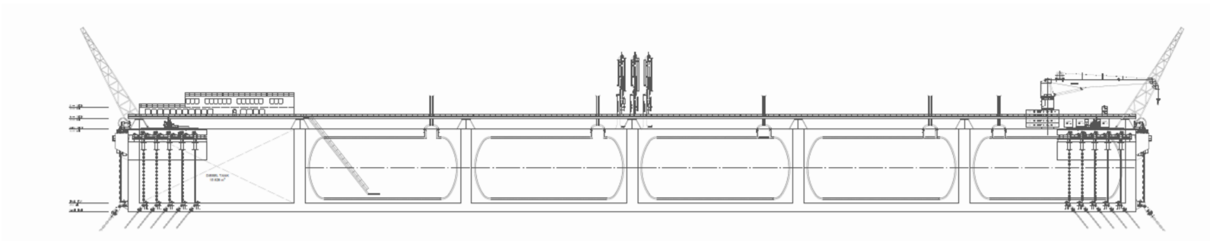


Figure 3 Case B

Simple formulas for the modularization concept design have been developed. Modularity have been used for liquid CO_2 storage tanks, liquefaction process plant, conditioning of dense phase CO_2 and onboard power generation. The interfaces and connections needed between a floating terminal and a ship and between the terminal and shore have been explored.

As a side activity, synergies between a FSRU and a floating CO_2 terminal have been explored. For an FSRU in the vicinity of a CO_2 terminal, the cold energy released during the vaporization of LNG can be utilized to liquefy CO_2. At the same time the CO_2 has been a heat source for evaporating LNG.

WP4 – Towards Zero Emission Shipping

Maritime transport is a key element in global trade and benefits from being one of the most energy efficient modes of transport. Still, the shipping industry accounts for about 3 % of the annual anthropogenic GHG emissions and emitted 1 076 Mt CO_2 in 2018, ref. (2).

The purpose of this report is to explore technologies that can enable low and zero emission shipping, where emission is limited to CO_2. The scope is further limited to emissions due to the shipping operation itself and limited to Scope 1 and 2 as defined by Greenhouse Gas Protocol. Here, Scope 1 are direct emissions from the core business (owned or controlled sources) and Scope 2 are indirect emissions from the generation of purchased energy consumed. There is a third category, Scope 3, representing all other indirect emissions that occur in the value chain, however these emissions are disregarded in this study. Illustrations of Scope 1, 2 and 3 emissions are shown in Figure 4.

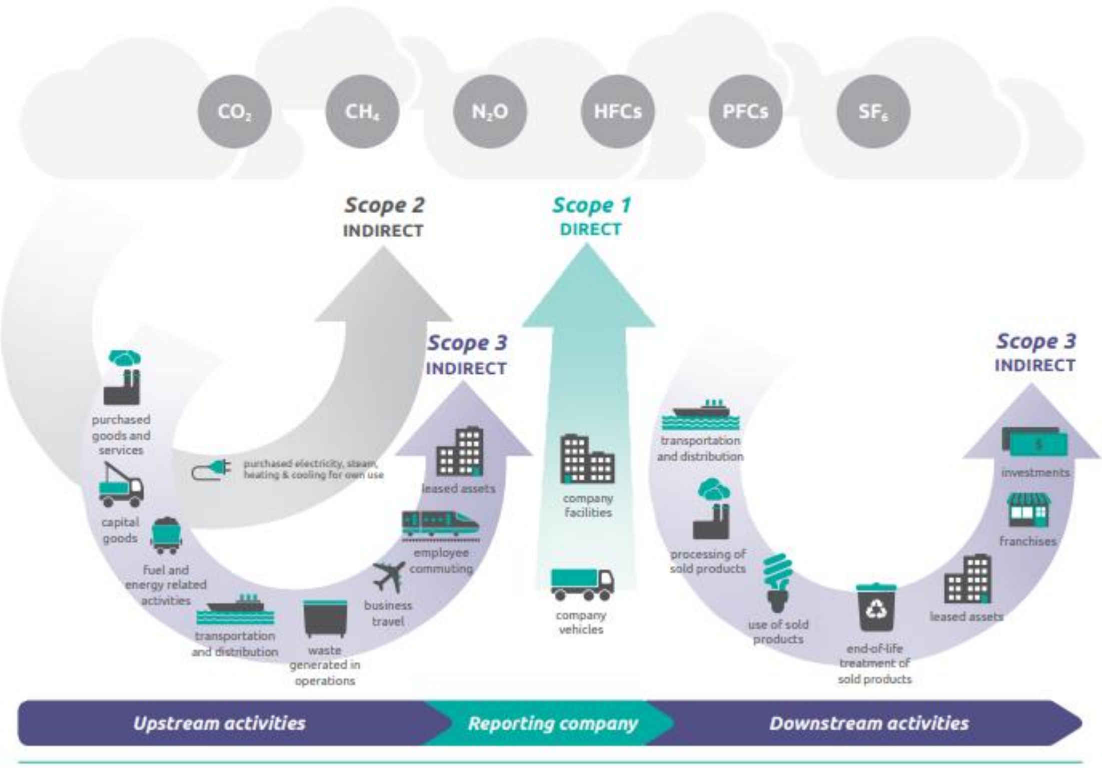


Figure 4 Illustration of Scope 1, 2, 3 emissions according to Greenhouse Gas Protocol, ref. (3)

Three main technology pathways have been discussed: ship optimization, fuel-switch, and onboard CO_2 capture. If zero emission is to be achieved, it is clear that a combination of different technologies needs to be implemented and ultimately it might also entail purchase of CO_2 offset credits. Low emission shipping on the other hand should be achievable either through onboard CO_2 capture, ship optimization, especially implementation of wind assistance technology, and fuel-switch (assuming that the fuel is generated from sustainable sources) alone. A remark in regard to all of these technologies is that the implementation of these should not result in any unwanted HSE (health, safety, and environment) aspects.

WP5 – Roadmap to Unmanned FSI

The term FSI is used within the CCS terminology as a short form for a Floating Storage and Injection Unit. When a CCS case encompasses ship transport and injection of CO_2 to an offshore storage reservoir, an FSI may be considered as a part of the logistics chain. The main purpose of including an FSI is to provide continuous injection into the reservoir. The FSI will be permanently located at the offshore injection site.

The FSI concept is often compared to the FPSO units in the oil and gas industry as they have many common features, such as cargo transfer with shuttle tanker, cargo storage in a displacement hull, process modules, well connection etc.

Crew of an FPSO can be in the range of 50-70 persons. With a two weeks on and four weeks off rotation the installation will require a workforce of 150-210 persons (less for an FSI du to less process equipment). Both from a commercial and a safety point of view it could be considered beneficial to reduce or remove the manning. Several initiatives have been made to map the opportunities and GAPs related to making FPSOs unmanned. SBM has issued a report as a contribution to this work package, ref. (4) where relevant subjects are highlighted, and lines drawn between FPSOs and the FSIs.

Based on ref. (4), other available sources and in-house competence on FPSO's and CO_2 logistics, a roadmap for the design of an unmanned FSI has been developed, ref. Figure 5.

A short Design Basis describing the main items for an unmanned FSI concludes this work package.

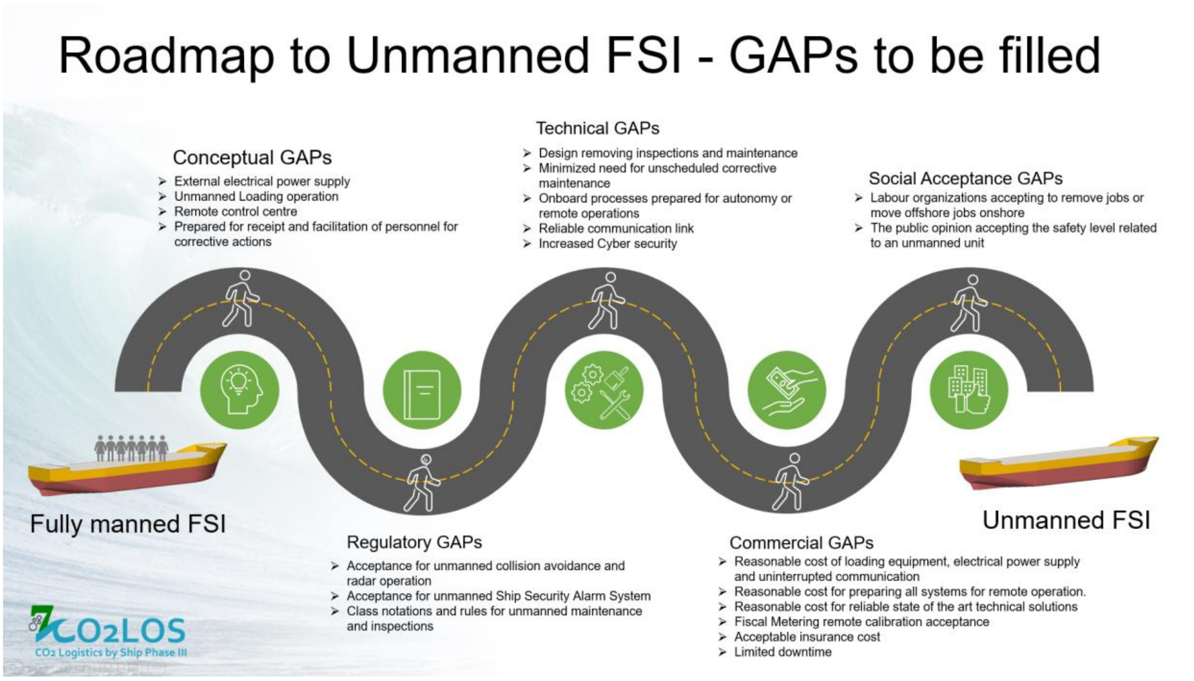


Figure 5 Roadmap to Unmanned FSI

WP6 – Potential for Batchwise Injection

Work Package 6 considers the potential for batchwise injection of CO_2 to underground reservoirs for permanent storage. This work package identifies potential showstoppers for batchwise CO_2 injection and new research in the area, aligning findings with other projects.

Batchwise CO_2 injection has been performed for many years in several projects but limited to pipeline transport of CO_2. The Huff'n Puff EOR operations in the US and permanent storage projects on the Norwegian Continental Shelf have all injected CO_2 periodically. In the EOR operations, the periodic CO_2 injection is part of the oil recovery strategy and at Sleipner and Snøhvit fields the periodic injection has happened due to operational reasons such as seasonal variations, maintenance- or modification tasks, well tests, workovers and treatments, equipment failures, weather conditions or intermittent CO_2 supply, ref. Figure 6.

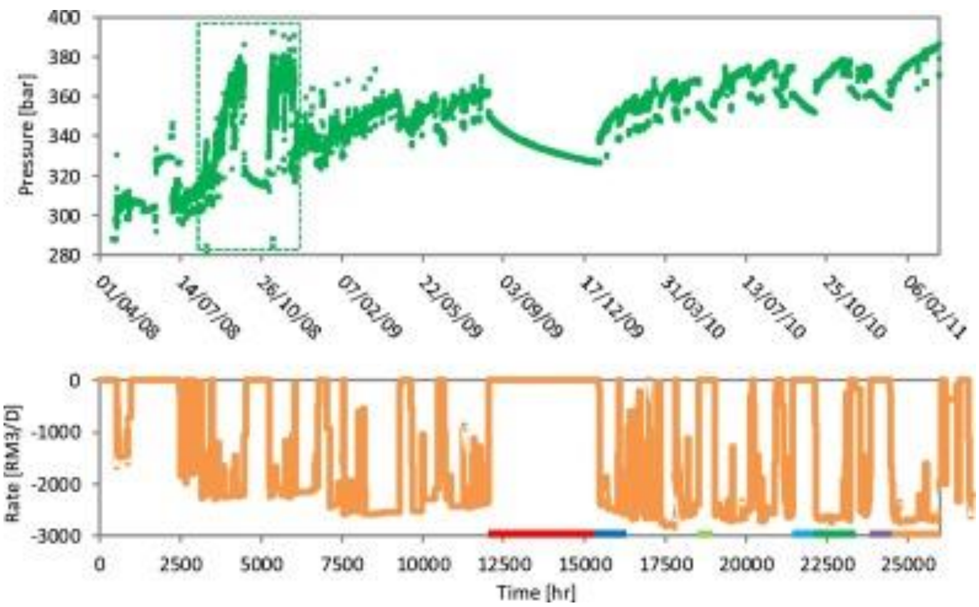


Figure 6: CO_2 injection pressure and rate into the Tubåen formation, at the Snøhvit field ref (5)

Batchwise injection gives variations in both temperature and pressure in the well and reservoir. The pressure and temperature will respond to the changes in different time scales- as the pressure changes are much faster than the temperature changes.

The work has the following conclusions:

'No major showstoppers have been identified, but there are some challenges that need to be addressed'

Some of the challenges are very case specific and may only be showstoppers in certain type of reservoirs, during very long disruptions in the injection flow or within specific temperature ranges for the CO_2. The main challenges that should be taken into account when considering batchwise injection of CO_2 are temperature variations, salt precipitation, back flow of brine phase and ice and hydrate formation.

WP7 – Rules and Regulations for CO_2 Shipping

This work package presents an overview of the rules and regulations governing the international carriage of CO_2 by ship, for the purpose of CCS. Carbon capture and storage (CCS) is a relatively new trade, so the governing rules and regulations are not yet fully developed. Work is ongoing, both internationally, and by flag states, to develop and implement rules and regulations governing the transport of CO_2 for storage, and for building ships for this purpose.

The report is organized in order of precedence:

- International law
- International regulations
- National state rules and regulations
- Classification society rules and regulations
- Industry associations

At the present time, several of the rules and regulations are under revision in order to be more specific to CO_2 transport.

INTRODUCTION

Carbon Capture and Storage is addressed by IEA as one of the key technologies in a scenario where net zero CO_2 emissions is reached by 2050 (NZE) and thus limiting the rise in global temperature to 1.5°C. In the NZE, 1.6 gigatonnes/y CO_2 will be captured by 2030, ramping up to 7.6 gigatonnes/y in 2050, ref. (6). This will require huge logistic operations. CCS/CCU transport has up to now mainly 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 by ships for decades, but these volumes are rather small compared to the planned CCS projects.

The scope of the CO2LOS III (CO_2 Logistics by Ship Phase III) project is to further increase the knowledge base for future ship based CCS projects logistics operations. The CO2LOS III project is a continuation of the CO2LOS II project and utilises relevant results from this project, ref. (7). As for CO2LOS II, the aim of the CO2LOS III project is to reduce the cost of CO_2 ship transportation by utilizing new technology and investigate optimization possibilities in the logistic chain.

The project consists of 7 work packages, each covering areas within CCS logistics where increased knowledge is believed to accelerate the development of future CCS projects. The work packages are:

- ✓ WP1 – Cost Estimation Tool for CCS Scenarios
- ✓ WP2 - Tank Arrangement for Large CO_2 Carriers
- ✓ WP3 – Floating CO_2 Terminals
- ✓ WP4 – Towards Zero Emission Shipping
- ✓ WP5 – Roadmap to Unmanned FSI
- ✓ WP6 – Potential for Batchwise Injection
- ✓ WP7 – Rules and Regulations for CO_2 Shipping

The Project started 1st of December 2021 with a duration of approximately 1.5 years.

This document is the public version of the final report documenting the CO2LOS III project. The report summarizes the non-confidential parts of the work performed.

WP1 – COST ESTIMATION TOOL FOR CCS SCENARIOS

1 INTRODUCTION

A parametric cost calculation model for CO_2 transport logistics for the purpose of comparing shipping and pipeline CCS scenarios is developed. The model enables the user to easily design a number of logistics solutions and calculate the associated CAPEX and yearly OPEX. Even combinations of pipeline and shipping transport may be calculated for multi step logistic chains. The tool does not include cost calculations for capture or storage. The results are presented as high level unclassified cost estimates, ref. Figure 7.

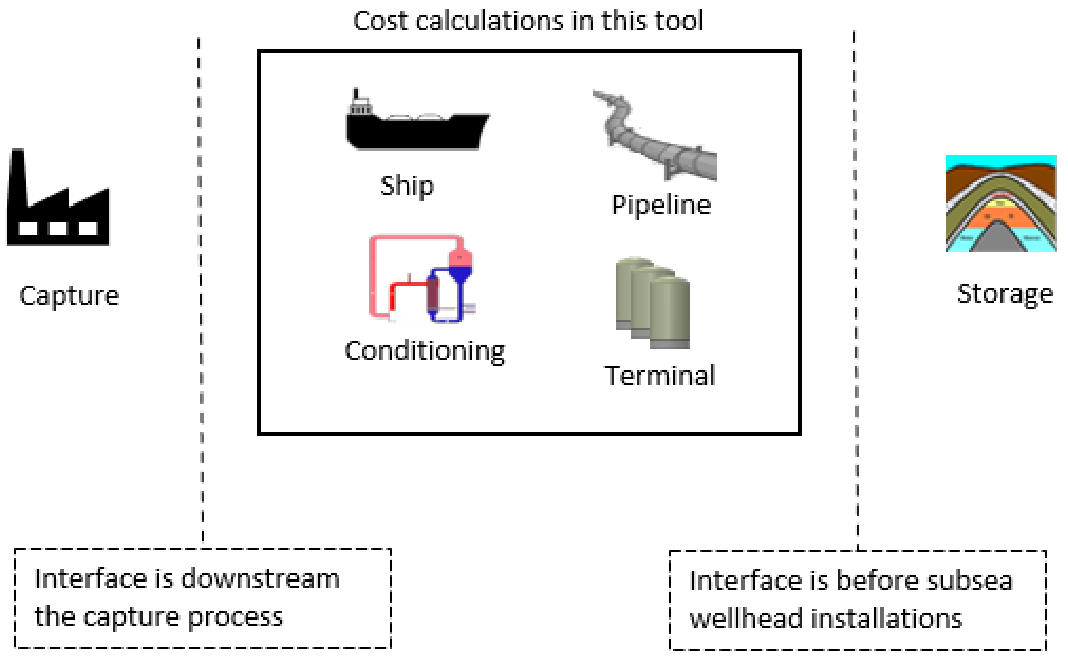


Figure 7 Scope of cost calculations and interfaces towards capture and storage

The model generates by bottom up approach, the physical elements of the specified CCS transport case. Engineered solutions are based on user and default (editable) input values such as locations, CO_2 stream, transport pressure, material, etc. Typically, pipeline diameter and wall thickness, number of ships, cargo capacity, ship size, number of cargo tanks, arrangement of cargo tanks and size of tanks are calculated.

The software is made by Brevik Engineering AS and SINTEF Industry in Porsgrunn. The tool is available for use to all Project partners but the property rights to the program lies with Brevik Engineering and SINTEF. The program itself is not publicly available.

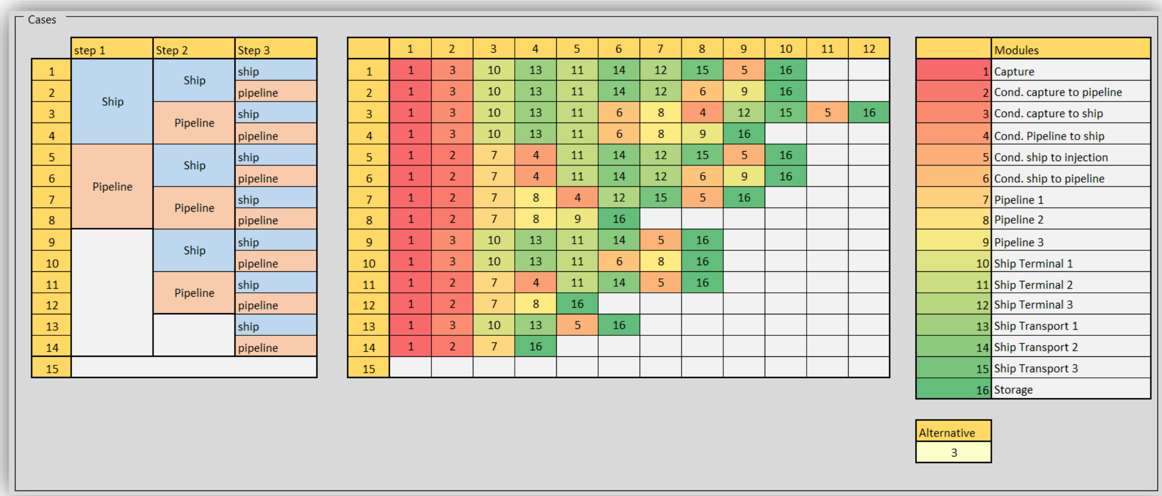
2 SOFTWARE ARCHITECTURE

The cost tool is a macro based, multi sheet excel workbook. The workbook contains the following sheets:

- Main – where main input is entered, and results presented
- Modules – gathers information from calculation sheets for presentation in Main sheet
- Inputs – tabularizes input from Main sheet for use in calculations
- Images – image bank for result presentation in Main sheet
- DistanceTablesEurope/Asia – tabular values of distances between locations
- Various calculation sheets (modules) – calculates the process and transport with associated costs

There are 10 unique calculation modules. The 10 modules are combined in 14 cases based on the Main sheet input, ref. Figure 8 and Figure 9. Each module will only appear one time in a case except from “Pipeline”, “Ship terminal” and “Ship transport” which may appear up to 3 times. This means the total number of modules needed are 16.

All modules are represented with a single sheet in the workbook, except “Ship transport” which consist of 2 sheets, one ship sheet and one tank sheet. Also, the program offers a Single Module Calculation which is not linked to the Main sheet input. In total, 30 calculation sheets are needed to cover all these functions .


Cases

	step 1	Step 2	Step 3
1	Ship	Ship	ship
2			pipeline
3		Pipeline	ship
4			pipeline
5	Pipeline	Ship	ship
6			pipeline
7		Pipeline	ship
8			pipeline
9		Ship	ship
10			pipeline
11		Pipeline	ship
12			pipeline
13			ship
14			pipeline
15			

	1	2	3	4	5	6	7	8	9	10	11	12
1	1	3	10	13	11	14	12	15	5	16		
2	1	3	10	13	11	14	12	6	9	16		
3	1	3	10	13	11	6	8	4	12	15	5	16
4	1	3	10	13	11	6	8	9	16			
5	1	2	7	4	11	14	12	15	5	16		
6	1	2	7	4	11	14	12	6	9	16		
7	1	2	7	8	4	12	15	5	16			
8	1	2	7	8	9	16						
9	1	3	10	13	11	14	5	16				
10	1	3	10	13	11	6	8	16				
11	1	2	7	4	11	14	5	16				
12	1	2	7	8	16							
13	1	3	10	13	5	16						
14	1	2	7	16								
15												

	Modules
1	Capture
2	Cond. capture to pipeline
3	Cond. capture to ship
4	Cond. Pipeline to ship
5	Cond. ship to injection
6	Cond. ship to pipeline
7	Pipeline 1
8	Pipeline 2
9	Pipeline 3
10	Ship Terminal 1
11	Ship Terminal 2
12	Ship Terminal 3
13	Ship Transport 1
14	Ship Transport 2
15	Ship Transport 3
16	Storage

Alternative
3

Figure 8 Calculation modules and case selection.

Macros are only used to provide the overall functionality of the program. Calculations within the different calculation modules are macro free.

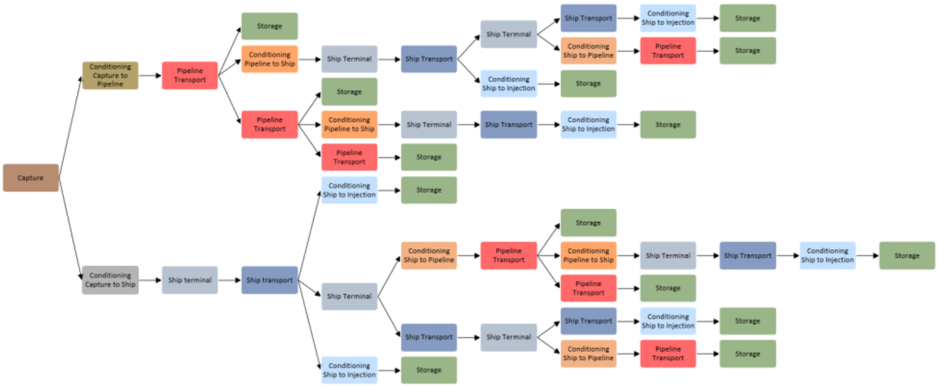


Figure 9 Flowchart, case selection

3 DESIGN BASIS

A comprehensive design basis describing the framework and parameters used in the calculation tool is a part of the work package delivery. In this public report the framework and selected parameters are included. Due to confidentiality reasons, cost data are not shown. Also detailed default parameters related to ship or pipeline transport are omitted.

3.1 Units

In general SI units apply for physical quantities. In addition, the units listed in Table 2 will be used.

Table 2 Non-SI Units

Property	Non-SI unit	SI unit	Ratio of Conversion
Pressure	bar[1]	Pa	1 [bar] is 100 000 [Pa]
Temperature	°C	K	x [°C] = (x + 273.15) [K]
Nautical Mile	nmi	m	1 [nmi] = 1852 m
Currency	€	not applicable	= used 1.1 $ or 10 NOK or 140 Yen

[1] For the purpose of this report barg (bar gauge) will be used, denoting the measured pressure, i.e. the pressure difference between the absolute pressure (bara) and the atmospheric pressure. Atmospheric pressure at sea level is approximately 1 bar.

3.2 General model framework

A framework limiting the use of the cost calculation tool is established. The purpose is to define a window for rate and distance minimum and maximum values in which the tool is expected to produce reasonable results. This window is considered wide enough to cover a wide range of CCS logistics scenarios. Locations in the two geographical areas Europe and Asia is selected for the first issue of the model.

Table 3 General model framework

Property	Value	Unit	Note
Capture, allowable range	0.4 – 15.0	Mt/y	

Property	Value	Unit	Note
Ship transport pressure	6.0 - 15.0	barg	Operating pressure
Distance, allowable range per step	10 - 12 000	km	1 km = 0.54 nm
Max steps in the logistics chain	3	-	Ship or pipeline
Available geographical areas	2	-	Europe and Asia

3.3 General default values

Default values for various parameters are used throughout the calculations. Some parameters are relevant for use in several modules and are as a default set to the same value. The LANG factor is used in the process industry to estimate the cost of new facilities. When the purchase price of all the process equipment is multiplied by the LANG factor, a rough estimate of the total installed cost of the plant, including equipment, materials, construction, and engineering is achieved.

3.4 Capture

The capture process is not a part of the cost calculation tool, however output values from the capture process such as the CO_2 stream outlet pressure and temperature are needed as input to the conditioning module for pipeline and ship. The capture module in the tool is only used to supply these values, which are selectable default values. No calculations of capture cost are performed.

Table 4 Capture

Property	Value	Unit	Note
Outlet pressure after Capture	0.01 or 0.80	barg	0.80 from amine capture system
Outlet temperature after Capture	30.0	°C	

3.5 Conditioning from capture to pipeline transport

After capture and before pipeline transport, conditioning of the CO_2 from gas phase to a liquid state at the minimum pipeline pressure of 80 barg and 5°C is assumed. Further pressurization to overcoming the pipeline pressure drop is included in the pipeline transport calculations.

Table 5 Capture to pipeline

Property	Value	Unit	Note
Inlet pressure	0.01 or 0.80	barg	0.80 from amine capture system
Inlet temperature	30.0	°C	
Outlet pressure	80.0	barg	
Outlet temperature	5.0	°C	

3.6 Conditioning from capture to ship transport

After capture and before ship transport, conditioning of the CO_2 from gas phase to a liquid state at the given operating pressure for the ship transport is assumed. Corresponding temperature is derived from the phase diagram saturation line, assuming liquid at equilibrium with vapour at the selected pressure.

Table 6 Capture to ship

Property	Value	Unit	Note
Inlet pressure	0.01 or 0.80	barg	
Inlet temperature	30.0	°C	
Outlet pressure	6.0 - 15.0	barg	Operating pressure
Outlet temperature	-	°C	Saturation line

3.7 Conditioning from pipeline to ship transport

Between pipeline transport and ship transport, conditioning of the CO_2 to the given operating pressure for the ship transport is needed. Corresponding temperature is derived from the phase diagram saturation line.

Table 7 Pipeline to ship

Property	Value	Unit	Note
Inlet pressure	80.0	barg	
Inlet temperature	5.0	°C	
Outlet pressure	6.0 - 15.0	barg	Operating pressure
Outlet temperature	-	°C	Saturation line

3.8 Conditioning from ship to pipeline transport

Between ship transport and pipeline transport, conditioning of the CO_2 to the minimum pipeline pressure of 80 barg and 5°C is needed. Further pressurization to overcome the pipeline pressure drop is included in the pipeline transport calculations.

Table 8 Ship to pipeline

Property	Value	Unit	Note
Inlet pressure	6.0 - 15.0	barg	Operating pressure
Inlet temperature	-	°C	Saturation line
Outlet pressure	80.0	barg	
Outlet temperature	5.0	°C	

3.9 Conditioning from ship transport to offshore injection

When performing offshore injection, conditioning the CO_2 from the ship transport pressure to the wellhead injection pressure is considered part of the logistics cost. This process plant is placed onboard the ship or FSI.

Table 9 Ship to injection

Property	Value	Unit	Note
Inlet pressure	6.0 - 15.0	barg	Operating pressure
Inlet temperature	-	°C	Saturation line
Outlet pressure	80.0	barg	
Outlet temperature	5.0	°C	

3.10 Pipeline transport

A simplified model for CO_2 pipelines has been developed.

Table 10 Pipeline basis for design

Property	Value	Unit	Note
Allowable pressure range	80 – 300	barg	Dense phase
Inlet temperature	5.0	°C	

3.11 Ship terminal with intermediate storage

A ship terminal is needed before and after a ship transport (unless when ending with offshore unloading). Intermediate storage is a part of the terminal.

Table 11 Ship terminal basis for design

Property	Value	Unit	Note
Intermediate storage vs ship size	1.2	-	

3.12 Ship transport

A module where the CO_2 transport ship is developed, including a sub module for tank calculations are a core part of the program. Due to confidentiality, this is not described further.

3.13 Storage

Wellhead inlet pressure is set to 80.0 barg. Further work may be to support input of wellhead inlet pressure i.e. in the range 80 - 200 barg.

Table 12 Storage basis of design

Property	Value	Unit	Note
Inlet pressure	80.0	barg	
Inlet temperature	5.0	°C	

4 LIMITATIONS IN THE PROGRAM

The results in the program should be used with caution. The main target of the tool development has been to provide CAPEX and OPEX for a given transport route with respectively pipeline or ship, for comparison purposes. Simplified models have been made for calculation of the different items forming the logistics chain. A selection of known limitations in the program is listed below.

- On a case by case basis, default values may be updated by the user to better fit the actual conditions in the specified case, if known.
- Items such as land cost, electricity cost, crew cost, construction cost etc is not linked to the selection of geographical area and selection of locations. An average of available cost data is used in the calculations. These costs are editable default values.
- Especially for onshore pipelines it may be challenging to establish a route. Length of the pipeline is adjusted with a factor multiplied with the aerial distance. This factor may be hard to establish, or the pipeline may even prove to be unrealistic to build. Construction cost is an editable default value.
- Size of ships may be too large as there will exist harbour limitations wrt draught, length etc. Max size of vessel is an editable default value.
- Cost of process plants equipment from ASPEN ref. (8), is from 2020 and no escalation for other years is included.
- A small number of inland locations connected to the sea by a waterway is selectable in the tool. The user must take care to select the appropriate destination by the sea. If the final destination also requires an open sea voyage, this should be a separate step since the program will calculate the cost of an inland vessel for the part of the voyage on the inland waterway.
- The pipeline transport calculation module uses editable default values for material, operating pressure and min/max velocity. The program does not iterate on these parameters to identify the lowest cost.
- Minimum number of ships is an editable default value in the Ship Transport calculation module. The program will always calculate with as few ships as possible fulfilling the logistics case and the minimum number of ships.
- Ship unloading time is an editable default value. Especially offshore unloading time may vary based on well injectivity, number of wells, size of vessel etc and should be checked for compatibility with the actual case if these parameters are known.
- If a scenario with short distance, high volume and several ships is selected, the ships may have to overlap each other when loading/unloading, resulting in a need for more than one quay, larger intermediate storage etc. This is not accounted for in the present version of the program.
- Tank calculations are based on simplified formulas.
- Pipeline calculations uses editable constants for the variable friction and density values.

5 CASE EXAMPLE

A case example could be assuming capture at a seaside facility in Antwerp with two storage options, either Johansen, 100 km off the coast from Bergen, Norway or at Nini West in Danish sector of the North Sea. Explored transport options are either offshore pipeline or ships with direct batchwise injection. Program plots are enclosed in Figure 10. In addition to the results shown, the program offers numerous detailed engineered solutions related to every case, such as size and number of ships, diameter of pipeline etc.

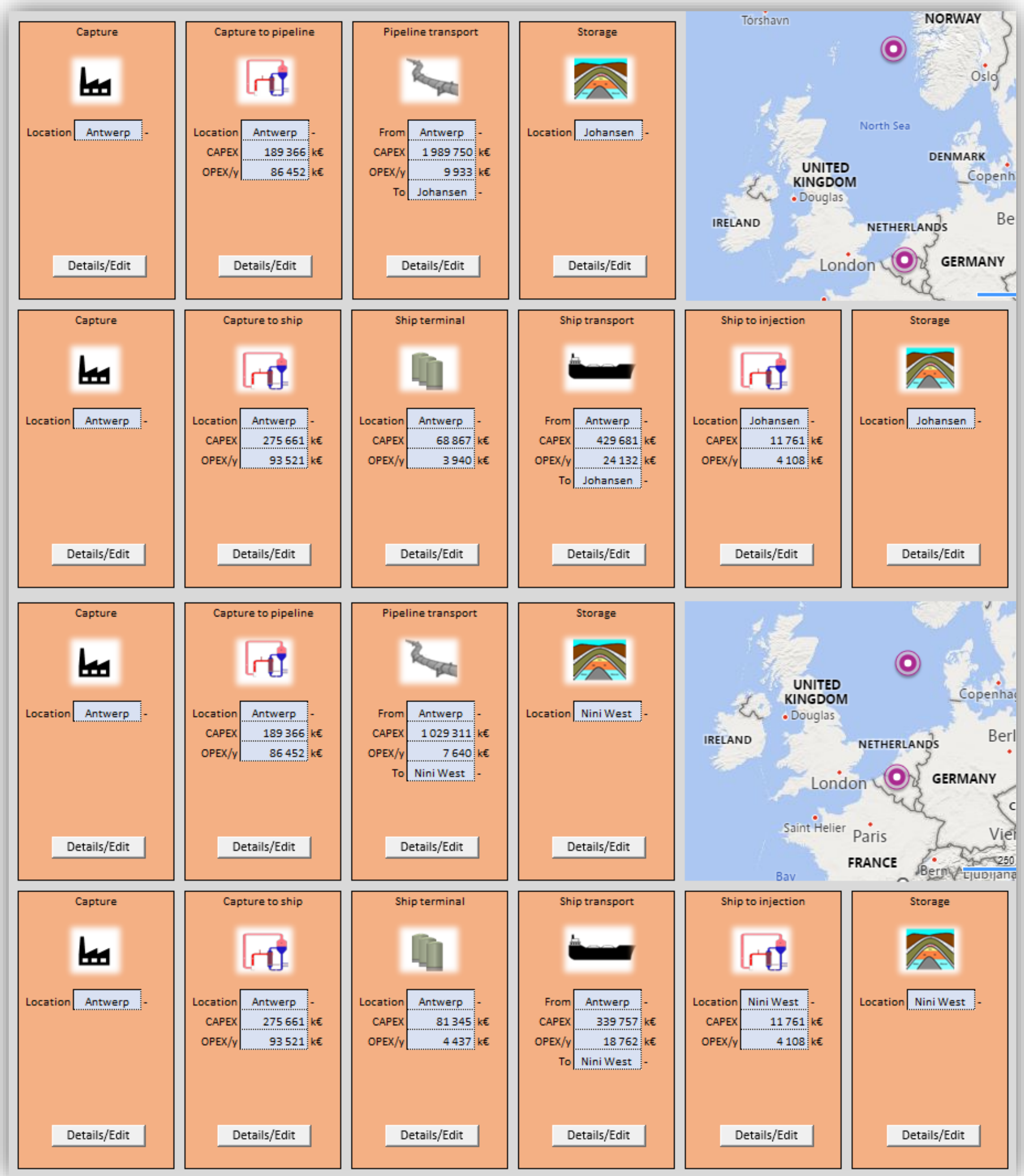


Figure 10 Example cases

WP2 – TANK ARRANGEMENT FOR LARGE CO_2 CARRIERS

1 INTRODUCTION

In this work package, the aim is to optimize ship designs for the carriage of large quantities of CO_2 over long distances, with low emission ships. The optimization begins with an investigation of the optimal pressure, in order to decide the possible tank dimensions for different tank forms. Possible tank arrangements are then considered, with regard to being suitable for a ship design with proportions optimized for low emissions. 3 sizes of ships are presented: 50 000 t, 80 000 t, and 150 000 t cargo capacity.

2 LP SWEET SPOT DETERMINATION

2.1 Properties of CO_2

CO_2 may occur as solid, gas and liquid depending on the pressure and temperature, see the phase diagram of CO_2 in Figure 11. In this work, the area from 6-10 barg is investigated to find the optimum design pressure for long distance ship transport. At atmospheric pressure and ambient temperature, the stable CO_2 phase is gas. The triple point (pressure 4.18 barg, temperature -56.6°C) is defined as the temperature and pressure where three phases (gas, liquid and solid) can co-exist in thermodynamic equilibrium. The definition of the operational pressure is the standard level of pressure at which a system is to operate. The design pressure is the mechanical design pressure of the tank. The pressure safety valves are set at this pressure. The difference is the safety margin where the pressure can change during the different stages in the transport chain.

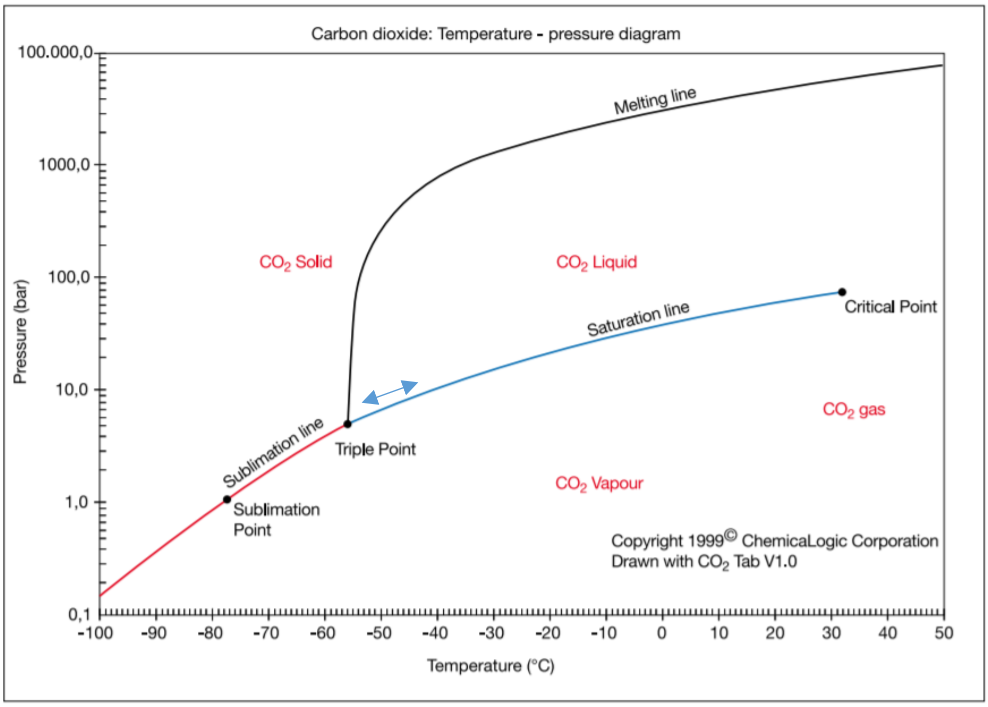


Figure 11 P-T diagram for CO_2 [7]

The temperature has a great impact on the density of liquid CO_2, which is important to identify the optimum pressure for ship transport. Higher density means that more CO_2 can be transported in the tankers. For liquid CO_2, the density increases when reducing the pressure due to the lower equilibrium temperature. The main reason for transporting at lower pressure, is the possibility to use larger tanks. Table 13 presents the different pressures, with corresponding temperatures and densities. The numbers are from the NIST chemistry WebBook SRD 69, ref. (9).

Table 13 Density of CO_2 at different conditions (liquid phase)

Pressure (barg)	Temperature (°C)	Density (kg/m3)
6	-49.4	1152,2
7	-46	1139.6
8	-42.9	1127.9
9	-40.1	1116.9
10	-37	1106
15	-28	1067.5

Impurities may have an impact on the phase diagram and density and should be taken into account when designing the CCS chain. This work has not investigated how different impurities will affect the behaviour of the CO_2. For example, could the water content have an impact on the choice of transport conditions, due to the possibility of hydrate formation and the fact that free water may cause corrosion. It is not expected from a transport pressure perspective, that impurities will have an impact on the choice of transport pressure from 6-10 barg and this is not discussed further in this report.

2.2 Key drivers

To determine the key drivers for selection of design and operational pressure, an investigation of safety, economic and operative issues have been performed. In the following chapters, these issues are identified and discussed.

2.2.1 Operational window

The operational window is determined by the maximum operational pressure and the lowest pressure possible, with a safety margin of 0.5 bar from the triple point, ref. (10). To avoid overpressure in the cargo tanks, safety valves are installed. The maximum allowable relief valve setting (MARVS), ref. (10) is often equal to the maximum allowable working pressure, MAWP, as defined in API 521, ref. (11). In this case MARVS=MAWP=mechanical design pressure as the outlet piping from PSVs on CO_2 tanks are short and without any bird-screens or similar, ref. (10). The maximum operating pressure is further limited by the typical simmering of the PSV, defined as audible or visible escape of compressible fluid between the seat and disc of a pressure-relief valve, ref. (12), which often happens prior to the PSV opening at the setpoint.

In the CO2LOS II project ref. (7), the design pressure was set at 7 barg, which resulted in a rather small margin-to the triple point at 4,18 barg. The absolute minimum operating pressure was 0.5 bar above the triple point, and due to the PSV, the maximum operational pressure was 6.8 barg ref. (7). By using these limitations, the operation window was very narrow, as shown in Figure 12 below.

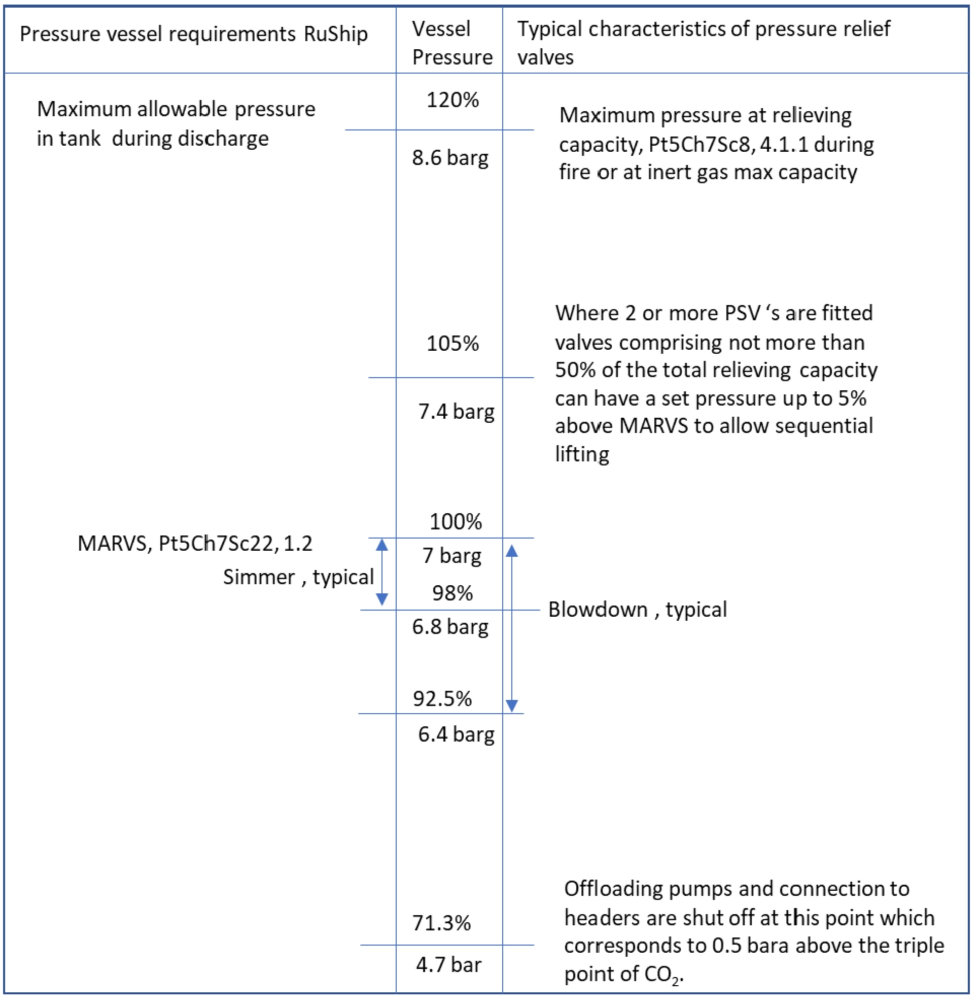


Figure 12 Pressure safety valve requirements and characteristics based on API 520 (12), fig. from CO2LOS II

Increasing the design pressure to 8.5 barg and the operation pressure to 7 barg results in an increase of the operational window and larger safety margins from the triple point, (See Figure 13 below). The absolute lowest pressure is here 4.7 barg where all inlets and outlets from the cargo tanks are closed. The exception being the pressure safety valves (PSV). A pre-alarm 0.3 bar above this is recommended to avoid this. A high alarm is foreseen at 8.2 barg which is 0.1 bar below the typical start of simmering by the PSVs.

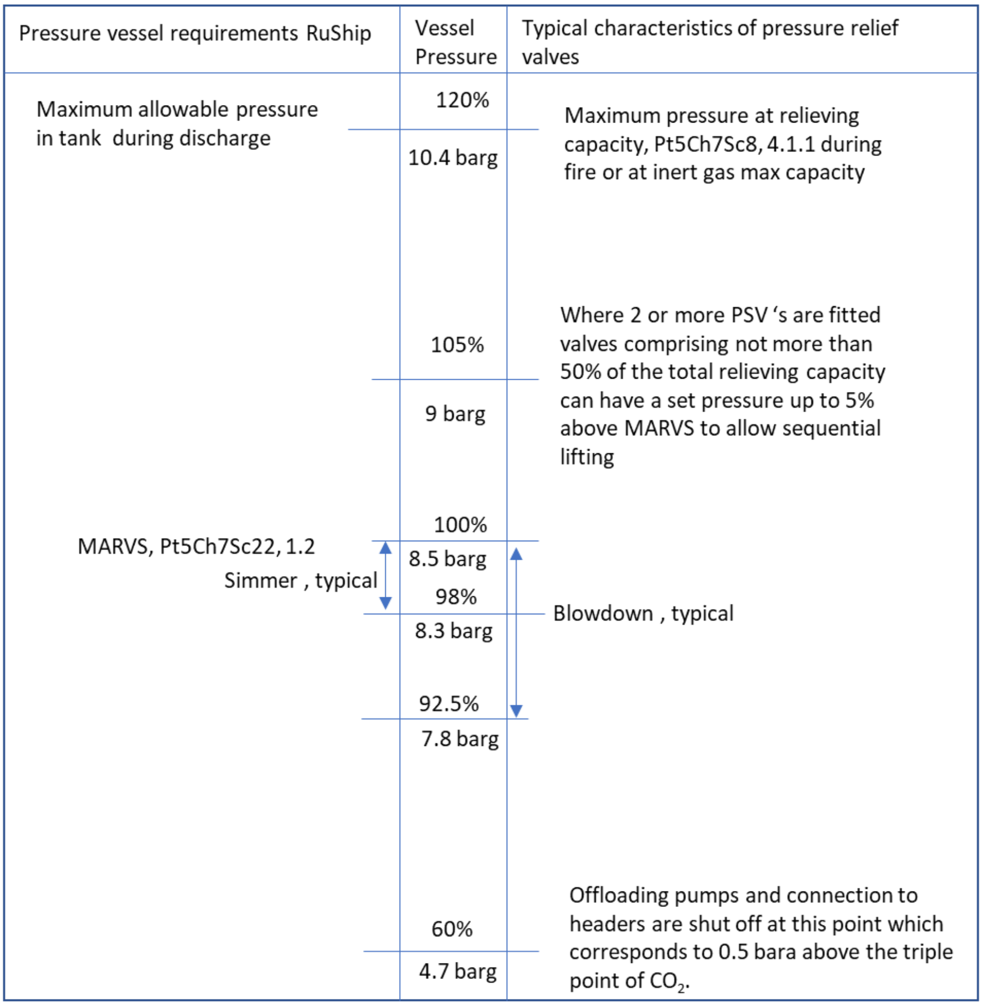


Figure 13 Pressure safety valve requirements and characteristics based on API 520 (12)

2.2.2 Technical readiness level (TRL)

There is currently no ship transport of CO_2 in the pressure range 6-10 barg. The ship transport today is by small ships at an operating pressure of 15-19 bar or in road transport tankers. The Northern Lights project ref. (13) plans to transport the CO_2 at operation pressure 13-18 barg, and that will demonstrate the medium pressure option in vessels of 7500m^3, and thereby increase the TRL for medium pressure. For low pressure, there is no demonstration project yet, and the TRL is low. There is no indication that the TRL differs between 6 to 10 barg, so the TRL is the same within that range.

2.2.3 Material choice

The low temperatures are a challenge for the material choice. According to the phase diagram, the pressure of 6 barg gives a temperature of –50°C, which is close to the limit for carbon manganese-steel. If higher pressure is used, the temperature is increased, and other materials are available and may reduce the material cost.

Table 14 Overview of different steel grades with minimum design temperature (7)

Grade DNVGL, BS ASTM or EN10028-3	Yield/Tensile 40 mm [MPa]	Elongation A5 %	Test temperature Charpy V at 40 mm	Minimum design temperature	Steel type	Manganese %
P355NL1	345/490	22%	-40°C	-20°C *	carbon-manganese	1.00-1.70
P355NL2	345/490	22%	-50°C	-30°C *	carbon-manganese	1.00-1.70
BS 1501 225 490B LT50	345/490	21%	-50°C	-30°C *	carbon-manganese	0.90-1.60
ASTM A203 F	380/485	20%	-60°C	-40°C	carbon-manganese	0.70-0.80
VL 2-4L	255/400	24%	-75°C	-55°C	carbon-manganese	0.70-1.60
VL 4-4L	325/490	21%	-75°C	-55°C	carbon-manganese	0.70-1.60
VL 0.5Ni/a	275/420	24%	-75°C	-55°C	0.5% nickel steel	0.70-1.50
VL 0.5Ni/b	345/490	22%	-75°C	-55°C	0.5% nickel steel	0.85-1.70
VL 1.5Ni/a	265/470	22%	-80°C	-60°C	1.5% nickel steel	0.30-1.50
VL 2.25Ni	295/500	22%	-85°C	-65°C	2.25% nickel steel	0.30.1.50
VL 3.5Ni	345/540	22%	-110°C	-90°C	3.5% nickel steel	0.30-0.70
VL 5Ni	380/570	21%	-125°C	-105°C	5% nickel steel	0.30-0.80
VL 9Ni	480/640	19%	-196°C	-165°C	austenitic 9%Ni steel	0.30-0.90
VL Mn 400	400/800	22%	-196°C	-165°C	austenitic manganese	22.50-25.50

* same margin for minimum design temperature relative to test temperature as for the DNVGL "VL" grades is assumed

The temperature difference between 6 and 10 barg is approx. 12°C, and there might be some other materials that could be used if the temperature is higher. It must be remembered that the minimum design temperature shall correspond to the equilibrium temperature for the lowest pressure reached during depressurization which is often the pressure of the ESD valves. The specific cost savings for this have not been investigated but it is assumed that with more choices, cost might be reduced.

2.2.4 Liquefaction

The purpose of the liquefaction plant is to convert the captured CO_2 to the transport conditions. There are two main methods for liquefying CO_2:

1. Internal cooling loop – here CO_2 is compressed to 70 barg and decompressed to transport pressure

2. External cooling loop – the CO_2 is compressed to transport pressure and cooled with an external cooling loop, e.g. by NH_3. Cooling the NH_3 is achieved through compression and decompression.

In CO2LOS II (7) it was suggested to first compress the CO_2 to 20 barg, then condense the CO_2 with cold NH_3 (external cooling loop), and then expand the CO_2 to the desired transport pressure. In the case of CO_2 decompression being part of the liquefaction method, not all the CO_2 is liquefied with some remaining in the gaseous phase. This gaseous CO_2 is flashed off and returned to the appropriate compression stage for recompression. The degree of flashing depends on the difference between start and final pressure, and the greater the difference, the higher the degree of flashing becomes. I.e. the flash volume is greater for 6 barg than for 10 barg and that gives slightly larger equipment and higher energy consumption.

2.2.5 Intermediate storage tanks

In the ship transport chain, intermediate storage is required both before and after the ship transport. The size of these storage tanks depends on the size of the ship and how often the ship arrives.

2.2.6 Tank design

The CO_2 tanks consist of an inner pressure vessel and an outer shell with insulation (for example polyurethane) in between. The intermediate storage tanks are normally arranged in a spherical, cylindrical vertical or horizontal configuration. Horizontal tanks may be easier to maintain, and the same tank geometry may be used both at ship and on land. Vertical tanks have smaller ground footprint, which is important for many industrial sites, and it is easier to accommodate expansion due to temperature changes. Spherical tanks are generally not that suitable for the large volumes needed in the CCS transport chain, as it would require a large area. In ref. (14) it is stated that it is common to cool down the CO_2 by a few degrees to reduce boil-off. It should be pointed out that this might not be a good idea if the pressure is close to the triple point.

2.2.7 Wall thickness

The wall thickness is determined by construction rules. With this restriction on wall thickness, the maximum diameter can be calculated based on the maximum allowed stress in the selected material and the pressure. This implies that for the same wall thickness, the volume of the tanks will be smaller with higher pressure.

2.2.8 Ship transportation

There are two aspects with the ship transport that should be considered, loading/unloading of the CO_2 and the cargo tanks for CO_2 in the ship.

2.2.8.1 Loading and unloading

Low-temperature hoses and pipes are available but have not been used for CO_2 at low pressure (-40 to -50 °C). Qualification of flexible hoses for low pressure CO_2 is ongoing and should be available in the near future. Flexible hoses for LPG exist, but the relevant temperature is higher, and CO_2 poses compatibility issues with rubber. Cryogenic hose for LNG exists today, but it is for lower pressure. Therefore, it is not expected that it is any specific difference within loading or unloading for the pressure ranges from 6 to10 barg.

In addition, the loading and unloading capacity of the ship is expected to be the same within this range. For CCS logistics, loading arms would be more likely than loading hoses, due to the large volumes in CCS.

There will be gas return from the ship during loading. In order to maintain pressure in the ship tanks the ship is not completely emptied during discharge. The volume of CO_2 that remains in the tanks is called tank heel and will be mostly CO_2 in gaseous phase. During loading, as the ship tanks are filled with liquid CO_2, the gas will be compressed and increase the pressure in the tanks. To avoid such a pressure increase, the gas is sent back to the intermediate storage tanks, via a gas return line. This

This project is co funded by CLIMIT. CLIMIT Project No. 618181

will also prevent the pressure in the intermediate storage tanks from dropping as the liquid is drained from the tanks and pumped into the ship. The tank heel mass volume is higher for 10 barg than for 6 barg.

2.2.8.2 Storage tanks onboard the ship

The wall thickness aspect is described in section 4.3.2. The same issues as for the land tanks will be valid for the tanks onboard the ship. In addition, if the wall thickness increases, the weight of the tanks rises. Weight is an important parameter for the ships, and therefore the lower pressure is even more beneficial than for tanks on land. The design of the tank is important for the ship to maximize the amount of CO_2 to be transported in one cargo.

If the pressure drops below the triple point, dry ice will form. It is necessary to keep the pressure and temperature within the range of design pressure and away from the triple point, to avoid this. DNV GL did a risk survey discussing the possibility of dry ice under low pressure conditions. The results show that the risk seems manageable by Emergency Shutdown Valves (ESD). ESD valves are a requirement for CO_2 ;DNV rules Ch 5, Pt7. Ch 19, ref. (10) and the lowest allowable pressure for these are 4.7 barg or 0.5 bar above the triple point for the cargo. As the low pressure gives lower temperatures, there may be an added risk of freezing of the surroundings. That should be taken into account when designing the equipment, but the risk is nearly equal whether the pressure is 10 or 6 barg as the temperatures are low for both.

2.3 Case study

The project has performed an exercise of how different design pressures from 7-10 barg will give extra challenges or extra benefits for each logistic element in a transport chain. A large CO_2 carrier (50 000 t) was cost estimated in CO2LOS II ref. (1) and has been chosen as the case ship in this work. The ship has a transport distance exceeding 1000 nautical miles, and a shore to shore trade is assumed. Delivery from capture site is at approx. 1 barg and 25°C, well injection pressure is appx 70 barg and 0°C. 20 years of operation is also used as the base case.

Each logistic element has been divided in sub elements and then the cost for the CO_2 carrier is distributed to each sub element, see Table 15. Some general elements like TRL level, risk of dry ice and choice of material has been included in the exercise but has not been cost estimated. Therefore, 20 % of the weighting has been distributed on these elements, and 80 % of the weighting is according to the share of the total cost.

If the chosen pressure has a benefit compared to a higher or lower pressure, the scoring has been given positive value from 1 to 3. If there are challenges with the chosen pressure, the scoring has been given negative values from -1 to -3. If we have not seen any specific challenges or benefits of the chosen pressure, the scoring has been set to 0.

Table 15 is an example showing the score based on current knowledge in the team. This is not a set answer for all cases, as that will vary according to the weighing of the elements done by those using it. I.e., if high CAPEX of intermediate storage is not considered a challenge, then perhaps the higher pressure is a better choice. Therefore, this is not a conclusion, but a tool for weighing the elements and an overview of how the different pressures scores in the sub elements in our exercise.

Table 15 Overview of case study results

				Low Pressure							
				10	*9,5*	*9,0*	*8,5*	*8,0*	*7,5*	*7,0*	**Not feasable to go this low**
				Points (from -3 to +3)							
Main element	Sub elements	Concept D [kEURO]	Score weight								
General	TRL level	-	6,0%	3	3	2	2	1	-1	-2	
	Risk of dry ice	-	3,0%	1	1	1	0	-1	-1	-1	
	Material		1,0%	1	1	1	0	0	-1	-1	
Liquefaction	Liquefaction CAPEX	223158	9,8%	1	1	0	0	-1	-1	-1	
	Liquefaction OPEX	342402	15,1%	1	1	1	1	0	-1	-1	
Intermediate storage (export terminal)	Intermediate Storage CAPEX	58480	2,6%	-3	-2	-1	0	1	2	3	
	Intermediate Storage OPEX	299	0,0%	0	0	0	0	0	0	0	
Loading	Process control transfer, risk of dry ice	-	4,0%	3	2	1	0	-1	-2	-3	
	Terminal and Loading equipment CAPEX	4745	0,2%	0	0	0	0	0	0	0	
	Terminal and Loading equipment OPEX	3032	0,1%	0	0	0	0	0	0	0	
Ship transport	Ship CAPEX	639930	28,2%	-1	-1	0	0	0	1	1	
	Ship OPEX	454720	20,0%	-1	-1	-1	0	1	1	1	
	Risk of boil-off during transit	-	2,0%	1	1	1	0	-1	-1	-1	
Unloading	Process control transfer, risk of dry ice	-	4,0%	3	2	1	0	-1	-2	-3	
	Terminal and Loading equipment CAPEX	4745	0,2%	0	0	0	0	0	0	0	
	Terminal and Loading equipment OPEX	3032	0,1%	0	0	0	0	0	0	0	
Intermediate Storage (import terminal)	Intermediate Storage CAPEX	58480	2,6%	-2	-1	-1	0	0	1	2	
	Intermediate Storage OPEX	299	0,0%	0	0	0	0	0	0	0	
Pre-treatment	Pretreatment prior to injection CAPEX	9000	0,4%	0	0	0	0	0	0	0	
	Pretreatment prior to injection OPEX	14000	0,6%	3	2	1	0	-1	-2	-3	
			Score:	0,14	0,10	0,17	0,27	0,05	0,02	-0,08	

As can be seen from the table, the highest middle score is the design pressure of 8,5 barg. That pressure has not many specific benefits or challenges but are the middle way compromising the benefits and challenges for higher and lower pressures.

2.4 Summary of findings

To investigate the sweet spot for ship transport at low pressure, both safety, operational and economic factors should be evaluated. It is not possible to find a general pressure that suits all CO_2 transport by ship, and the aim of the summary table is to show how the changes in pressures and temperature affects these elements. The table below summarizes our findings.

Table 16 Summary of safety, operational and economical aspects with changes in transport pressure

Transport chain element	Safety issues	Operational issues	Economic issues
Overall elements	Risk of dry ice is present, and a safety margin to the triple point should be taken into account and favours higher pressure	No operational issues are favouring either 6 or 10 barg	More materials may be utilized with higher temperature, and that may reduce the cost. In favour of higher pressure.

Transport chain element	Safety issues	Operational issues	Economic issues
Liquefaction		Lower pressure leads to more CO_2 to be handled with the return flash.	Slightly larger equipment and higher energy consumption with 6 barg compared to 10 barg
Intermediate storage onshore	Risk for dry ice is present, and a safety margin to the triple point should be taken into account.	No operational issues are favouring either 6 or 10 barg	Less steel with low pressure according to wall thickness The liquid density is higher at lower pressure, mainly due to the lower equilibrium temperature. The increased density allows for increased load of CO_2 with the same tank volume.
Ship transportation	Risk for dry ice is present, and a safety margin to the triple point should be taken into account.	Larger operational window with higher pressure, and might be more risk to have boil off with low pressure	Less steel with low pressure and lower weight Lower pressure enables larger tanks which is more economical Less " tank heel" with lower pressure

2.5 Recommended pressure and temperature

Based on the investigation done in this report, a design pressure of 8.5 barg and a maximum operational pressure of 7 barg is recommended for large ship carriers of CO_2 used in the CO2LOS projects. This reflects the desire to go closer to the triple point to reduce weight and increase the volume that can be handled on each trip, and also the need for considering the safety issues when operating close to the triple point. There should also be a safety range from the operation pressure to the design pressure to allow for safety valves to have a margin. In general, the pressure will increase during the different stages in the logistic chain. It is therefore advisable to use material and equipment that can handle a pressure range of 6 – 10 barg, with corresponding temperatures. This gives a robust design and a transport chain that can be utilized in several scenarios.

3 TANK DESIGNS FOR SWEET SPOT LP

3.1 Cargo tank design

3.1.1 Scope of work

The scope of work in this chapter is to calculate the main dimensions for CO_2-tanks based on the temperature and pressure specification from Chapter 2 - LP Sweet Spot Determination, with the following shapes:

- Horizontal cylindrical tank
- Vertical cylindrical tank
- Bilobe tank
- Trilobe tank
- Spherical tank
- Prismatic tank

Prescriptive rules have been used to calculate the dimensions of the cylindrical tanks, but the other tank shapes are not covered by these rules. These calculations are therefore made on a conceptual level.

Based on the chosen material, scope of work is to design as large as possible cargo tank limiting the thickness of the material to 50 mm. IACS has issued a revised IACS UR W1(in force from July 2022) ref (15) providing test requirements for plates above 40 mm with an upper limit of 50 mm. The project will make use of this UR and aim for a shell thickness of 50 mm for the development of tank designs.

3.1.2 Rules and regulations

Pressure vessel design calculations has been done in accordance with applicable rules and guidelines. The DNV rules are based on the IGC code and will cover these requirements.

- DNV – Rules for Classification of Ships Pt.5 Ch.7 Liquified Gas Tankers ref. (16)
- DNV – Rules for Classification of Ships Pt.4 Ch.7 Pressure Equipment, ref. (17)
- DNV – Rules for Classification of Ships Pt.2 Ch.2 Metallic Materials, ref. (18)
- DNV-CG-0135 Liquified gas carriers with independent cylindrical tanks of type C, ref. (19)
- International Maritime Organization – International Code for the Construction and Equipment of Ships Carrying Liquified Gases in Bulk, ref. (20)
- IACS UR W1 - Material and welding for ships carrying liquefied gases in bulk and ships using gases or other low-flashpoint fuels ref. (15)

3.1.3 Units

In general SI units apply. In addition, where in line with normal practice, rules applied or relevant standards, the units listed in Table 17 will be used.

Table 17 Non-SI Units

Property	Non-SI unit	SI unit	Ration of Conversion
Pressure	bar[1]	Pa	1 [bar] is 100 000 [Pa]
Temperature	°C	K	x [°C] = (x + 273.15) [K]

[1]For the purpose of this report barg (bar gauge) will be used, denoting the measured pressure i.e. the pressure difference between the absolute pressure (bara) and the atmospheric pressure. Atmospheric pressure at sea level is approximately 1 bar

3.1.4 Coordinate system

A right-handed cartesian coordinates system is applied:

Longitudinal: X, positive forward from AP

Transverse: Y, positive towards portside from CL

Vertical: Z, positive upwards from BL

3.1.5 Input for CO_2-tank calculations

General input for CO_2-tank calculations is found in Table 18.

Table 18 Input for tank calculations

Parameter	Symbol	Value
Design pressure	P_0	8.5 barg
Design cargo temperature (min)	T_{cargo}	-55°C
Density of cargo (liquid CO_2 at -55°C)	ρ_c	1.173 t/m^3
CO_2 purity		*ref Northern Lights specification

3.1.6 Characteristic data used for calculation of ship accelerations

The scope of work is to design different cargo tanks for arrangement on ships of total cargo capacity of 50 kt, 80 kt and 150 kt. Design accelerations will change for the different vessel sizes and arrangements. It is assumed that the highest accelerations will be for the smallest vessel, therefore accelerations for the 50 kt carrier are chosen for the initial tank design. The vessel dimensions are based on an initial cargo block of 190 m x 34 m.

Table 19 Characteristic data for ship

Parameter	Symbol	Value	Rule reference
Ship Rule Length	L	255.0 m	(21) Section 4
Breadth	B	42.5 m	(21) Section 4

Parameter	Symbol	Value	Rule reference
Draught	T	9.7 m	(21) Section 4
Block Coefficient	C_B	0.8 (-)	(21) Section 4
Depth	D	25.5 m	(21) Section 4
Service Speed	V	12.0 knots	

3.1.7 Materials and allowable stresses

Two different materials have been used in the calculations, NV 4-4L and NV 5Ni/a. Main parameters for these materials are found in Table 20 and Table 21. For the material selection, it has been looked at several pressure vessel steel qualities applicable for low temperatures. The prices and complexity of the production process of the materials, and limitation to tank sizes due to design vapor pressure have been factors for the selection.

Table 20 Material NV 4-4L

Parameter	Symbol	Value	Rule reference
Material	NV 4-4L		
Tensile strength, min.	σ_B	490 MPa	(18) Section 3, Table 14
Yield stress, thickn. > 16 < = 40 (mm)*	σ_F	325 MPa	(18) Section 3, Table 14
Minimum design temperature for NV 4-4L		-55°C	(18) Section 3, Table 14
Factor "A" for carbon-manganese steel	A	3	(16) Section 22, 2.8
Factor "B" for carbon-manganese steel	B	1.5	(16) Section 22, 2.8
Allowable stress parameter based on yield strength	σ_B/A	163.3 MPa	(16) Section 22, 2.8
Allowable stress parameter based on tensile strength	σ_F/B	216.7 MPa	(16) Section 22, 2.8
Allowable stress parameter	f	163.3 MPa	(16) Section 22, 2.8
Equivalent von Mises primary general membrane stress	$\sigma_m \leq f$	163.3 MPa	(16) Section 22, 2.8

* Yield stress for thickness up to 50 mm should be verified.

Table 21 Material NV 5Ni/a

Parameter	Symbol	Value	Rule reference
Material	NV 5Ni/a		
Tensile strength, min.	σ_B	570 MPa	(18) Section 3, Table 15
Yield stress, thickn. > 16 < = 40 (mm)*	σ_F	380 MPa	(18) Section 3, Table 15
Minimum design temperature for NV 5Ni/a		-105°C	(18) Section 3, Table 15
Factor "A" for carbon-manganese steel	A	3	(16) Section 22, 2.8
Factor "B" for carbon-manganese steel	B	1.5	(16) Section 22, 2.8
Allowable stress parameter based on yield strength	σ_B/A	190.0 MPa	(16) Section 22, 2.8

Parameter	Symbol	Value	Rule reference
Allowable stress parameter based on tensile strength	σ_F /B	253.3 MPa	(16) Section 22, 2.8
Allowable stress paramenter	f	190.0.MPa	(16) Section 22, 2.8
Equivalent von Mises primary general membrane stress	$\sigma_m \leq f$	190.0 MPa	(16) Section 22, 2.8

* Yield stress for thickness up to 50 mm should be verified.

3.1.8 Results

Based on a mechanical design pressure 8.5 barg and minimum design cargo temperature of -55°C, ref. (2), and a limiting material thickness of 50mm, the following main dimensions of cargo tanks have been estimated:

Table 22 Tank calculation results

Tank shape	Volume	Main Dimensions	Material
Horizontal cylindrical	9 082 m^3	Outer Diameter: 13.7m Tank length: 65.0m	NV 4-4L
Horizontal cylindrical	8 641 m^3	Outer Diameter: 15.2m Tank length: 51.0m	NV 5Ni/a
Vertical cylindrical	2 848 m^3	Outer Diameter: 11.5m Tank height: 30.0m	NV 4-4L
Vertical cylindrical	3 108m^3	Outer Diameter: 14.0m Tank height: 23.0m	NV 5Ni/a
Bilobe tank	15 130 m^3	Lobe outer diameter: 13.0m Length: 65.0m Width: 22.5m	NV 4-4L
Bilobe tank	15 545 m^3	Lobe outer diameter: 15.0m Length: 51.0m Width: 25.9m	NV 5Ni/a
Trilobe tank	16 873 m^3	Lobe outer diameter: 12.5m Length: 65.0m Width: 21.4m	NV 4-4L
Trilobe tank	16 428 m^3	Lobe outer diameter: 14.0m Length: 51.0m Width: 24.0m	NV 5Ni/a
Spherical tank	8 083m^3	Outer Diameter: 25.0m	NV 4-4L
Spherical tank	6 287m^3	Outer Diameter: 23.0m	NV 5Ni/a
Prismatic tank, free form pressure tank	15 431m^3	Length: 43.0m Width: 24.0m Height: 16.0m	NV 4-4L

4 CARGO BLOCK DESIGN

4.1 Cargo block arrangement

For the design of cargo blocks, a tank filling of 97% and cargo density of 1.139 t/m^3 has been used. Tanks from chapter 3.1.8 are used as is or downscaled to better fit in the cargo block. As described in ref. (22), minimum distance of 380 mm between curved tank shells and 600 mm between flat surfaces are used between the tanks. 200 mm around the tanks are reserved for tank insulation. To design a cargo block layout for a vessel suitable for slow speed and with no area restrictions, the following parameters are attempted to be satisfied:

- Length of cargo block is approximately 75% of the ship LPP
- Moulded depth of vessel is approximately 1/10 of the ship rule length
- Length to width ratio L/B of the ship close to but not below 5.5 (max 8)

Cargo blocks with the tank alternatives in chapter 3.1.8 are made for the three vessel sizes. Results are summarized in Table 23, Table 25 and Table 27. Colour codes according to traffic lights colour scheme are used to reflect the scoring from the selection matrixes in Table 24, Table 26 and Table *28*.

Beam, length and draught restrictions i.e. due to harbour limitations has not been applied as these are case specific parameters. However typically for a given draught restriction the volume utilisation of the selected arrangement may prove to be too high due to the high density of the cargo and the additional weight of the tanks.

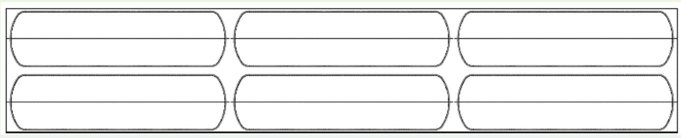
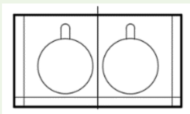
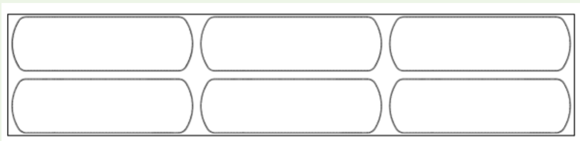
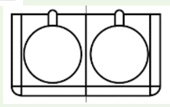
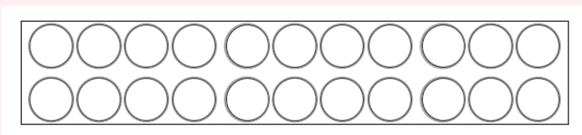
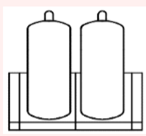
4.2 Selection matrix

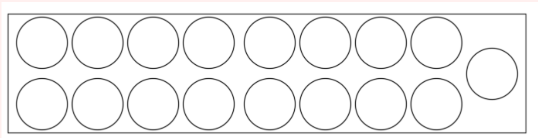
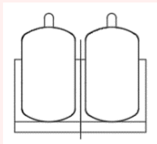
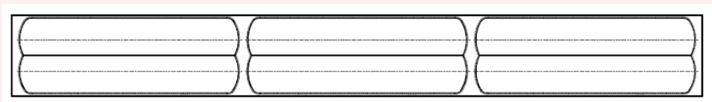
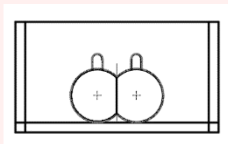
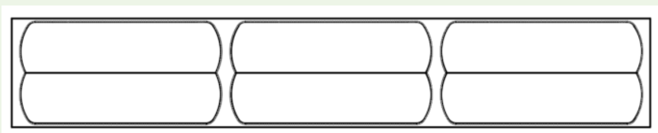
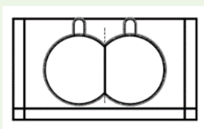
The selection matrix ranks each cargo block alternative solution based on the selected criteria. The total score of each solution is the sum of scores for each criterion multiplied by the criteria weight factor. The design with the highest weighted total score is the most suitable for the selected cargo vessel.

- For the 50 000 t cargo vessel, the highest weighted total score is for the horizontal cylindrical tanks with material NV 5Ni/a.
- For the 80 000 t cargo vessel, the highest weighted total score is for the prismatic scalable tank
- For the 150 000 t cargo vessel, the highest weighted total score is for the spherical tanks with material NV4-4L.

4.2.1 50 000 t cargo vessel

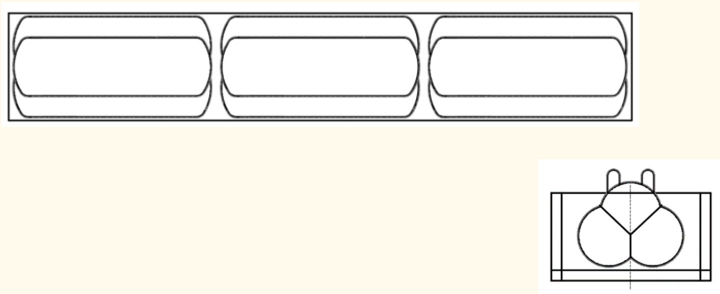
Table 23 Summary 50 000t vessel

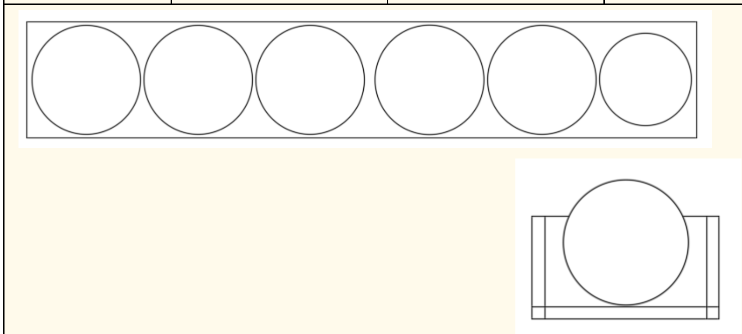
Tank description	Cargo Area	Vessel size	No of tanks Dimension	Evaluation Matrix
Horizontal cylindrical NV 4-4L	171.3m x 31.4m	228m x 41.5m	6 D=13.7m L=54.7m	**Cargo block utilization [Score 2]** Main deck will have to be lowered. **Efficient ship structure [Score 1]** Lower main deck, length to width reduced. Medium size ship. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 24**
 				
Horizontal cylindrical NV 5Ni/a	157.2m x 33.6m	210.0m x 38.1m	6 D=15.2m L= 45m	**Cargo block utilization [Score 2]** High utilization of cargo block. **Efficient ship structure [Score 2]** Efficient structure, medium size ship. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 28***
  *Selected for ship design				
Vertical cylindrical NV 4-4L	127.8m x 24.0m	170.4m x 31.0m	22 D=10.0m H=30.0m	**Cargo block utilization [Score 1]** Tank height high compared to main deck level. **Efficient ship structure [Score 1]** Main deck level will have to be increased a lot. Height of tanks could give problems with vessel stability. Small vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 0]** High number of tanks **Weighted total score: 15**
 				

<table>
<tr><td>Vertical cylindrical
NV 5Ni/a</td><td>131.3m x 30.0m</td><td>175.0m x 31.8m</td><td>17
D=13.0m
H=23.0m</td><td rowspan="2">Cargo block utilization [Score 1]
Tank height high compared to main deck level.
Efficient ship structure [Score 1]
Main deck level will have to be increased a lot. Height of tanks could give problems with vessel stability. Small vessel size.
Complexity of construction [score 2]
Low complexity
Number of tanks/equipment cost [score 0]
High number of tanks
Weighted total score: 15</td></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Bilobe
NV 4-4L</td><td>204.0m x 24.1m</td><td>272.0m x 49.5m</td><td>3
D=13.0m
L=65.0m
B=22.5m</td><td rowspan="2">Cargo block utilization [Score 0]
Low utilization of the cargo block.
Efficient ship structure [Score 1]
Main deck level and length to width ration will have to be reduced Not possible with centre bulkhead. Large vessel size.
Complexity of construction [score 1]
Medium complexity
Number of tanks/equipment cost [score 2]
Low number of tanks
Weighted total score: 11</td></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Bilobe
NV 5Ni/a</td><td>162.0m x 27.5m</td><td>216.0m x 39.3m</td><td>3
D=15.0m
L=51.0m
B=25.9m</td><td rowspan="2">Cargo block utilization [Score 2]
High utilization of the cargo block.
Efficient ship structure [Score 2]
Length to width ration will have to be lowered. Not possible with centre bulkhead. Medium vessel size.
Complexity of construction [score 1]
Medium complexity
Number of tanks/equipment cost [score 2]
Low number of tanks
Weighted total score: 25</td></tr>
<tr><td colspan="4"> </td></tr>
</table>

<table>
<tr><td>Trilobe
NV 4-4L</td><td>183.0m x 23.0m</td><td>244.0m x 44.4m</td><td>3
D=12.5m
L=58.7.0m
B=21.4m</td><td rowspan="2">Cargo block utilization [Score 1]
Medium utilization of the cargo block.
Efficient ship structure [Score 1]
Main deck level and length to width ration will have to be lowered. Not possible with centre bulkhead. Large vessel size.
Complexity of construction [score 0]
High complexity
Number of tanks/equipment cost [score 2]
Low number of tanks

Weighted total score: 13</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Trilobe
NV 5Ni/a</td><td>149.3.0m x 25.6m</td><td>200.0m x 36.4m</td><td>3
D=14.0m
L=47.4m
B=24.0m</td><td rowspan="2">Cargo block utilization [Score 2]
High utilization of the cargo block.
Efficient ship structure [Score 1]
Main deck level must be increased, length to width ration reduced. Not possible with centre bulkhead. Medium vessel size.
Complexity of construction [score 0]
High complexity
Number of tanks/equipment cost [score 2]
Low number of tanks

Weighted total score: 18</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td>Sphere
NV 4-4L</td><td>154.2m x 26.6m</td><td>206.0m x 37.4m</td><td>6
D=25.0m</td><td rowspan="2">Cargo block utilization [Score 1]
Medium utilization of the cargo block.
Efficient ship structure [Score 1]
Main deck level must be increased, length to width ration reduced. Not possible with centre bulkhead. Medium vessel size.
Complexity of construction [score 2]
Low complexity
Number of tanks/equipment cost [score 2]
Low number of tanks

Weighted total score: 19</td></tr>
<tr><td colspan="4"></td></tr>
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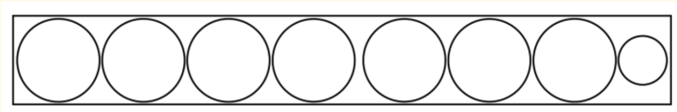
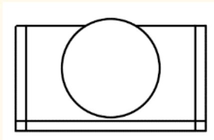
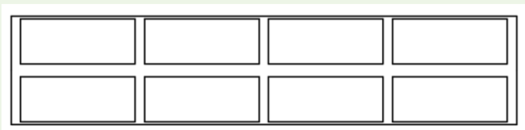
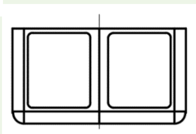
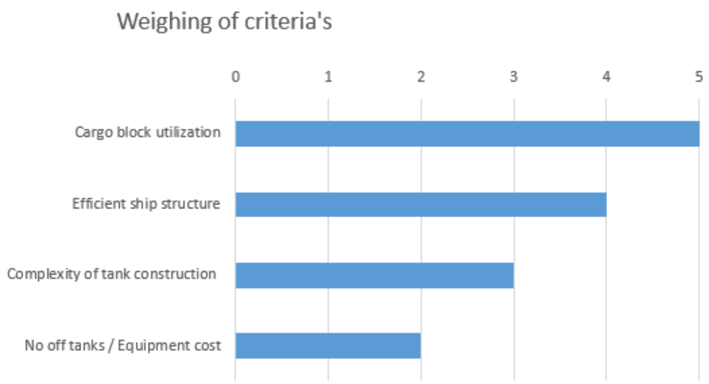
Sphere NV 5Ni/a	184.1m x 24.6m	245.0m x 44.0m	8 D=23.0m	**Cargo block utilization [Score 1]** Medium utilization of the cargo block. **Efficient ship structure [Score 2]** Main deck level must be increased, length to width ration reduced. Not possible with centre bulkhead. Large vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 1]** Medium number of tanks Weighted total score: 21
 				
Prismatic	141.0m x 30.1m	188.0m x 34.5m	8 L=32.0m B=12.5m H=15.0m	**Cargo block utilization [Score 2]** High utilization of the cargo block. **Efficient ship structure [Score 2]** Efficient ship structure if the weight of tank structure does not make a problem for the design. Small vessel size. **Complexity of construction [score 1]** Unknown complexity of tank design **Number of tanks/equipment cost [score 1]** Medium number of tanks Weighted total score: 23
 				

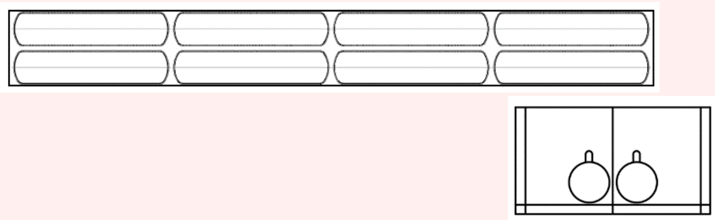
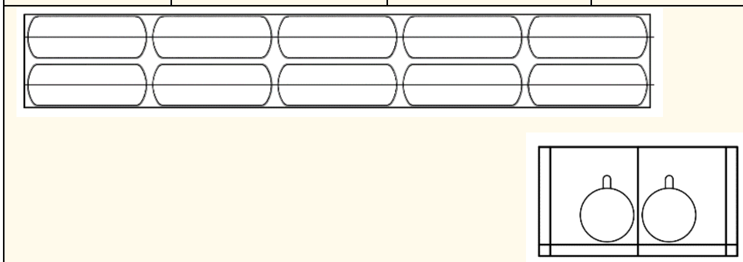
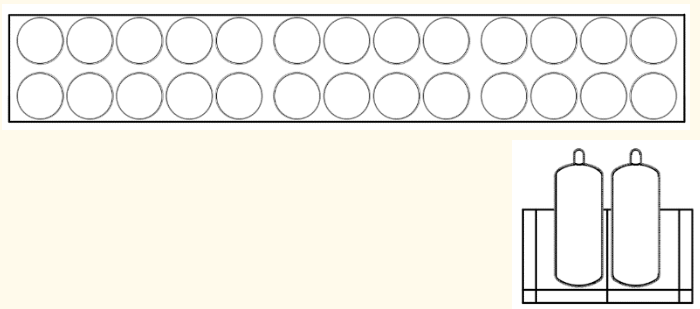
Table 24 Selection matrix for 50 000 t vessel

50 000t vessel			**Score**										
Criteria	**Weight (1-5)**	**Scoring scheme**	**Horizontal cylindrical NV 4-4L**	**Horizontal cylindrical NV 5Ni/a**	**Vertical Cylindrical NV 4-4L**	**Vertical Cylindrical NV 5Ni/a**	**Bilobe NV 4-4L**	**Bilobe NV 5Ni/a**	**Trilobe NV 4-4L**	**Trilobe NV 5Ni/a**	**Sphere NV 4-4L**	**Sphere NV 5Ni/a**	**Prismatic**
Cargo block utilization	5	Low = 0, Medium = 1, High = 2	2	2	1	1	0	2	1	2	1	1	2
Efficient ship structure	4	Low = 0, Medium = 1, High = 2	1	2	1	1	1	2	1	1	1	2	2
Complexity of tank construction	3	Low = 2, Medium = 1, High = 0	2	2	2	2	1	1	0	0	2	2	1
No off tanks / Equipment cost	2	Low = 2, Medium = 1, High = 0	2	2	0	0	2	2	2	2	2	1	1
Total	**14**	**Weighted total score**	**24**	**28**	**15**	**15**	**11**	**25**	**13**	**18**	**19**	**21**	**23**



4.2.2 80 000 t cargo vessel

Table 25 Summary 80 000t vessel

Tank type	Cargo Area	Vessel size	No of tanks Dimension	Evaluation
Horizontal cylindrical NV 4-4L	271.4m x 31.4m	361.0m x 65.6m	8 D=13.7m L=65.0m	**Cargo block utilization [Score 0]** Low utilization of the cargo block. **Efficient ship structure [Score 0]** Main deck level and length to width radio must be reduced. Large vessel size. **Complexity of construction [score 2]** Low complexity of tank design **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 10**
				
Horizontal cylindrical NV 5Ni/a	232.0mx34.4m	309.0mx56.2m	10 D=15.2 L=44.0m	**Cargo block utilization [Score 0]** Low utilization of the cargo block. **Efficient ship structure [Score 1]** Main deck level and length to width radio must be reduced. Medium vessel size. **Complexity of construction [score 2]** Low complexity of tank design **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 14**
				
Vertical cylindrical NV 4-4L	171.1mx27.0m	228.0m x 41.5m	26 D=11.5m H=30.0m	**Cargo block utilization [Score 1]** Tank height high compared to main deck level. **Efficient ship structure [Score 1]** Main deck level will have to be increased a lot. Height of tanks could give problems with vessel stability. Small vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 0]** High number of tanks **Weighted total score: 15**
				

<table>
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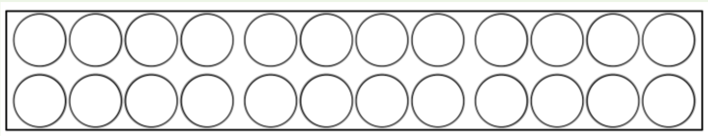
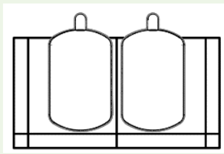
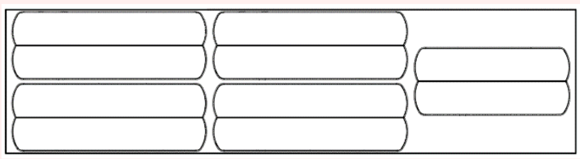
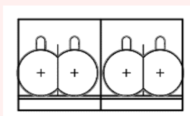
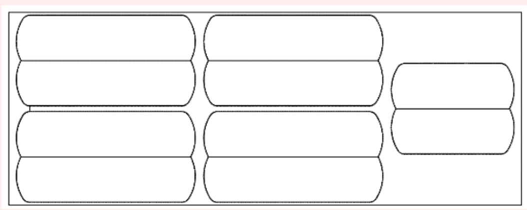
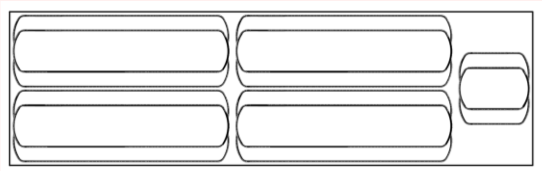
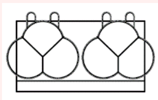
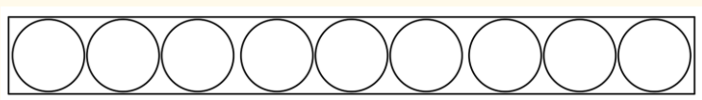
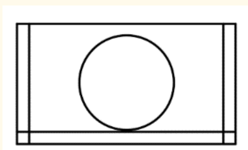
NV 5Ni/a</td><td>188.5mx32.0m</td><td>251.0m x 45.6m</td><td>24
D=14.0m
H=23.0m</td><td rowspan="2">Cargo block utilization [Score 2]
High utilization of cargo block.
Efficient ship structure [Score 2]
Main deck level will have to be increased, length to width ratio decreased. Small vessel size.
Complexity of construction [score 2]
Low complexity
Number of tanks/equipment cost [score 0]
High number of tanks

Weighted total score: 24</td></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Bilobe
NV 4-4L</td><td>191.0mx48.2m</td><td>255.0m x 46.3m</td><td>5
D=13.0m
L=65.0m
B=22.5m</td><td rowspan="2">Cargo block utilization [Score 0]
Low utilization of cargo block.
Efficient ship structure [Score 0]
Short and wide vessel, main deck level will have to be lowered.
Complexity of construction [score 1]
Medium complexity
Number of tanks/equipment cost [score 2]
Low number of tanks

Weighted total score: 7</td></tr>
<tr><td colspan="4"> </td></tr>
<tr><td>Bilobe
NV 5Ni/a</td><td>146.0mx55.0m</td><td>195.0 m x35.5m</td><td>5
D=15.0m
L=51.0m
B=25.9m</td><td rowspan="2">Cargo block utilization [Score 0]
Low utilization of cargo block.
Efficient ship structure [Score 0]
Short and wide vessel, main deck level will have to be lowered,
Complexity of construction [score 1]
Medium complexity
Number of tanks/equipment cost [score 2]
Low number of tanks
Weighted total score: 7</td></tr>
<tr><td colspan="4"></td></tr>
</table>

Trilobe NV 4-4L	158.2m x 46.4m	211.0m x 38.4m	5 D=12.5m L=65.0m B=21.4m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 0]** Short and wide vessel, main deck level will have to be increased, **Complexity of construction [score 0**] High complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 4**
 				
Trilobe NV 5Ni/a	N/A	N/A	5 D=14.0m L=51.0m B=24.0m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 0]** Short and wide vessel, main deck level will have to be increased, **Complexity of construction [score 0**] High complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 4**
Sphere NV 4-4L	237.2m x 26.6m	316.0m x 57.5m	9 D=25.0m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 1]** Length to width ratio will have to be decreased. Large vessel size. **Complexity of construction [score 2**] Low complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 14**
 				

<table>
<tr><td>Prismatic</td><td>167m x 34.6m</td><td>223.0m x 40.5m</td><td>8
L=38.5m
B=14.5m
H=18.0m</td><td rowspan="2">Cargo block utilization [Score 2]
High utilization of the cargo block.
Efficient ship structure [Score 2]
Efficient ship structure if the weight of tank structure does not make a problem for the design. Small vessel size.
Complexity of construction [score 1]
Unknown complexity of tank design
Number of tanks/equipment cost [score 2]
Low number of tanks

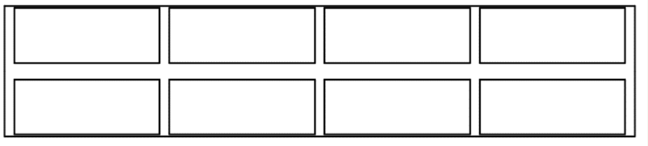
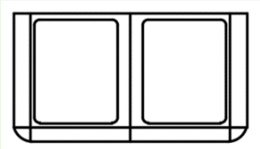
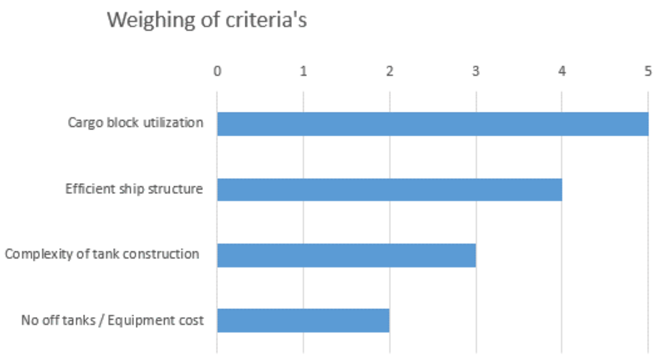
Weighted total score: 25*</td></tr>
<tr><td colspan="4">

*Selected for ship design</td></tr>
</table>

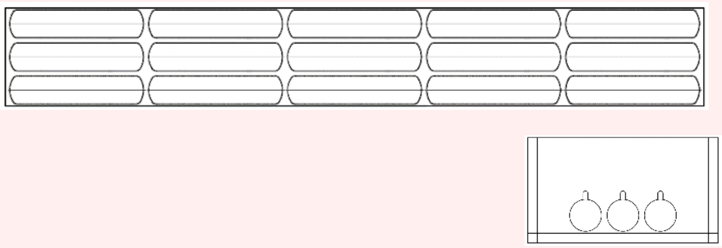
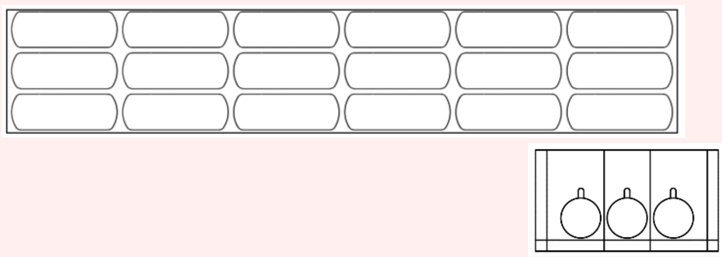
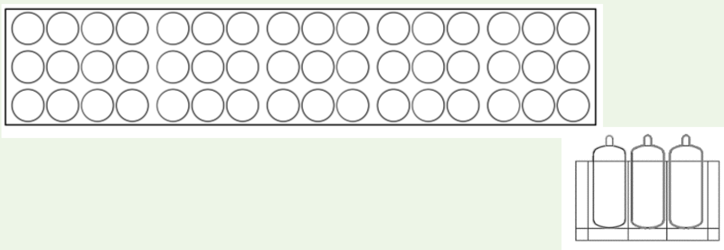
Table 26 Selection matrix for 80 000 t vessel

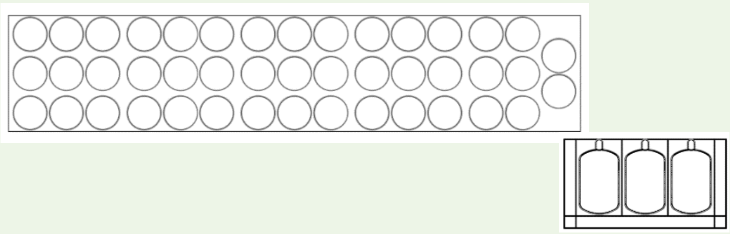
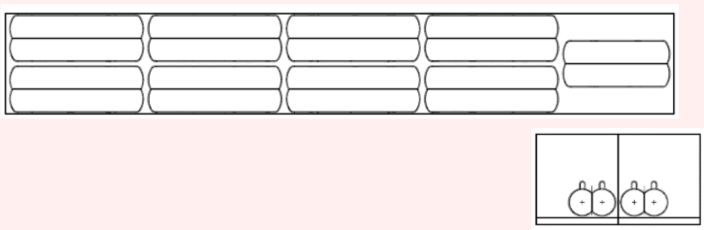
80 000t vessel			Score									
Criteria	**Weight (1-5)**	**Scoring scheme**	**Horizontal cylindrical NV 4-4L**	**Horizontal cylindrical NV 5Ni/a**	**Vertical Cylindrical NV 4-4L**	**Vertical Cylindrical NV 5Ni/a**	**Bilobe NV 4-4L**	**Bilobe NV 5Ni/a**	**Trilobe NV 4-4L**	**Trilobe NV 5Ni/a**	**Sphere NV 4-4L**	**Prismatic**
Cargo block utilization	5	Low = 0, Medium = 1, High = 2	0	0	1	2	0	0	0	0	0	2
Efficient ship structure	4	Low = 0, Medium = 1, High = 2	0	1	1	2	0	0	0	0	1	2
Complexity of tank construction	3	Low = 2, Medium = 1, High = 0	2	2	2	2	1	1	0	0	2	1
No off tanks / Equipment cost	2	Low = 2, Medium = 1, High = 0	2	2	0	0	2	2	2	2	2	2
Total	**14**	**Weighted total score**	**10**	**14**	**15**	**24**	**7**	**7**	**4**	**4**	**14**	**25**

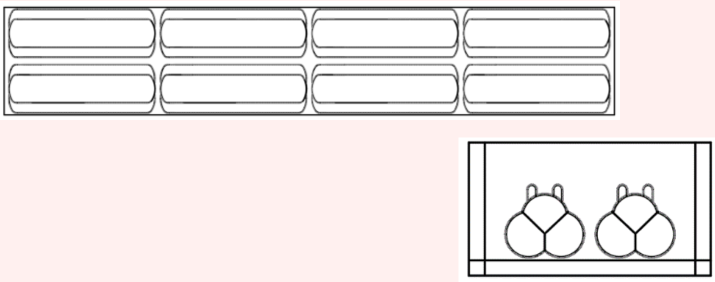
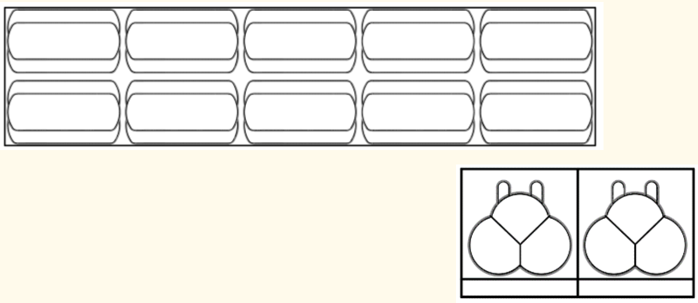
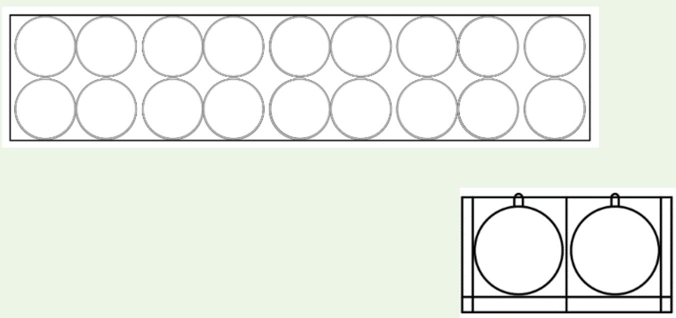


4.2.3 150 000 t cargo vessel

Table 27 Summary 150 000t vessel

Tank type	Cargo Area	Vessel size	No of tanks Dimension	Evaluation
Horizontal cylindrical NV 4-4L	338.8m x 47.5m	451.0m x 82.0m	15 D=13.7m L=65.0m	**Cargo block utilization [Score 0]** Low utilization of the cargo block. **Efficient ship structure [Score 0]** Main deck level and length to width radio must be reduced. Large vessel size. **Complexity of construction [score 2]** Low complexity of tank design **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 10**
				
Horizontal cylindrical NV 5Ni/a	287.2m x 52.4m	383.0m x 69.6m	18 D=15.2m L=45.2m	**Cargo block utilization [Score 0]** Low utilization of the cargo block. **Efficient ship structure [Score 0]** Main deck level and length to width radio must be reduced. Large vessel size. **Complexity of construction [score 2]** Low complexity of tank design **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 10**
				
Vertical cylindrical NV 4-4L	213.7m x 41.8m	285.0m x 51.8m	48 D=11.5m H=30.0m	**Cargo block utilization [Score 2]** High utilization of cargo block. **Efficient ship structure [Score 2]** Main deck level will have to be increased. Small vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 0]** High number of tanks **Weighted total score: 24**
				

Vertical cylindrical NV 5Ni/a	238.0m x 45.2m	317.0m x 57.6m	44 D=14.0m H=23.0m	**Cargo block utilization [Score 2]** High utilization of cargo block. **Efficient ship structure [Score 2]** Small vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 0]** High number of tanks, **Weighted total score: 24**
				
Bilobe NV 4-4L	325.8m x 49.0m	433.0m x 78.7m	9 D=13.0m L=65.0m B=22.5m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 0]** Short and wide vessel, main deck level will have to be lowered. **Complexity of construction [score 1]** Medium complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 7**
				
Bilobe NV 5Ni/a	N/A	N/A	9 D=15.0m L=51.0m B=25.9m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 0]** Short and wide vessel, main deck level will have to be lowered. **Complexity of construction [score 1]** Medium complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 7**

Trilobe NV 4-4L	271.4m x 47.6m	362.0m x 65.8m	8 D=12.5m L=65.0m B=21.4m	**Cargo block utilization [Score 0]** Low utilization of cargo block. **Efficient ship structure [Score 0]** Main deck level and length to width radio must be reduced. Large vessel size. **Complexity of construction [score 0]** High complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 4**
				
Trilobe NV 5Ni/a	227.0m x 52.8m	302.0m x 54.9m	10 D=14.0m L=43.0m B=24.0m	**Cargo block utilization [Score 1]** Medium utilization of cargo block. **Efficient ship structure [Score 1]** Main deck level must be reduced, breadth of vessel is not sufficient for side structure. Small vessel size. **Complexity of construction [score 0]** High complexity **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 13**
				
Sphere NV 4-4L	241.0m x 52.1m	321.0m x 58.3m	18 D=24.5m	**Cargo block utilization [Score 2]** High utilization of cargo block. Tank diameter can be adjusted to fit cargo block. **Efficient ship structure [Score 2]** Small vessel size. **Complexity of construction [score 2]** Low complexity **Number of tanks/equipment cost [score 1]** Medium number of tanks **Weighted total score: 26***
 *Selected for ship design				

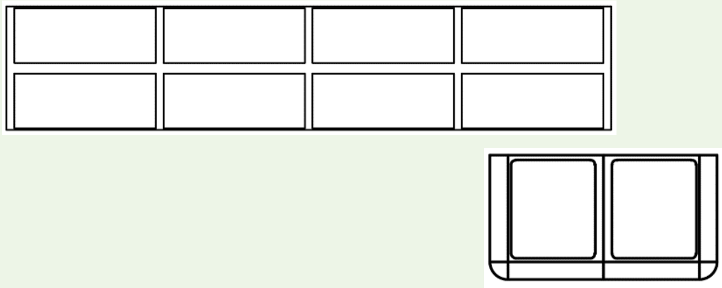
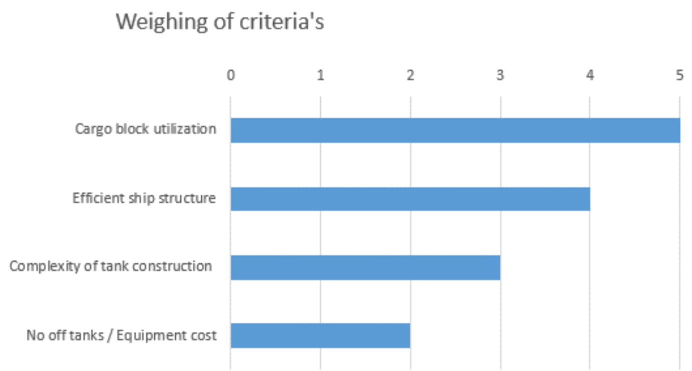
Prismatic	200.2m x 40.9m	267.0m x 48.5m	8 L=46.8m B=18.0m H=21.0m	**Cargo block utilization [Score 2]** High utilization of the cargo block. **Efficient ship structure [Score 2]** Efficient ship structure if the weight of tank structure does not make a problem for the design. Small vessel size. **Complexity of construction [score 1]** Unknown complexity of tank design **Number of tanks/equipment cost [score 2]** Low number of tanks **Weighted total score: 25**
				

Table 28 Selection matrix for 150 000 t vessel

150 000t vessel			Score									
Criteria	**Weight (1-5)**	**Scoring scheme**	**Horizontal cylindrical NV 4-4L**	**Horizontal cylindrical NV 5Ni/a**	**Vertical Cylindrical NV 4-4L**	**Vertical Cylindrical NV 5Ni/a**	**Bilobe NV 4-4L**	**Bilobe NV 5Ni/a**	**Trilobe NV 4-4L**	**Trilobe NV 5Ni/a**	**Sphere NV 4-4L**	**Prismatic**
Cargo block utilization	5	Low = 0, Medium = 1, High = 2	0	0	2	2	0	0	0	1	2	2
Efficient ship structure	4	Low = 0, Medium = 1, High = 2	0	0	2	2	0	0	0	1	2	2
Complexity of tank construction	3	Low = 2, Medium = 1, High = 0	2	2	2	2	1	1	0	0	2	1
No off tanks / Equipment cost	2	Low = 2, Medium = 1, High = 0	2	2	0	0	2	2	2	2	1	2
Total	**14**	**Weighted total score**	**10**	**10**	**24**	**24**	**7**	**7**	**4**	**13**	**26**	**25**



5 CONCEPTUAL SHIP DESIGNS

5.1 General Concept

Based on the cargo block selection from chapter 4.2, ship designs are developed for 3 different cargo capacities: 50 000 t, 80 000 t, and 150 000 t capacity. Tank arrangements for 3 ships are presented. During the design work, the selected cargo section for the 150 000 t ship (spherical tanks) were discarded and an alternative tank shape with vertical bilobe tanks selected for the final design. The designs are optimized for low emissions by the methods explained in the following chapter.

5.1.1 Hull shape

The hull shape to be optimized for slow steaming.

$L/B \approx 6$

$Fn \approx 0.11$

$C_b \approx 0.85\text{-}0.875$.

A bulbous bow is not efficient for the relevant Fn and C_b. In addition, building cost will be reduced without a bulb.

LCB for minimum power requirement; 2.8-3.1 % of Lpp forward of midship.

A long run, providing:

- Adventitious waterflow to propeller.
- Space for emission reducing devices.
- Space for adding equipment as new technologies mature.
- The use of appropriate energy saving devices, to achieve synergistic effects

5.1.2 Ship layout

The ship lay out will be driven by:

- The feasibility of the tank design in relevant size.
- The tank design impact on the hull shape and its hydrodynamics.
- Ship main dimensions for the payload.
- Structural integrity of the ship.

As default, the ships will be built with a double bottom, and double sides. This is not a requirement of the IGC code for type 3 gas carriers but will probably be required for ballast, when sailing with no cargo, and for buoyancy when sailing fully loaded. This arrangement will also be advantageous for controlling collision damage.

5.1.3 Propulsion

The main propulsion system is chosen for low emissions and fuel consumption. The routes will be straight forward, and higher maneuverability than for normal cargo ships, is not required. The chosen propulsion system, in all cases, is a low speed, 2-stroke, dual fuel engine, directly coupled to the propeller shaft. Auxiliary propulsion may be provided by Flettner rotors, to reduce fuel consumption and/ or to allow the main engine to use a power take-off for generating electricity. If the Flettner rotors are chosen, the propeller should be of the controllable pitch type, so that the engine may run at the optimal rpm. This will allow the engine to run a shaft generator when the rotors are contributing to the power.

5.1.4 Energy saving Devices

Several energy saving devices shall be fitted to the vessel, to increase propulsive efficiency and reduce fuel consumption. For these vessels the chosen devices are, ref. (23):

- Wake equalizing duct
- Kappel design propeller
- Rudder bulb
- High efficiency rudder

Assuming these are designed to work together, a reduction if fuel consumption of approximately 10% may be achieved, ref. (23).

There will also be an option to install air lubrication.

5.1.5 Stability

At this stage of design, stability is checked by stipulating that the GM, checked by regression formulas, shall be greater than 1.2 m, ref. (24).

5.2 Ship design 50 000 t Cargo Capacity

5.2.1 Arrangement

The ship has 6 horizontal cylindrical tanks arranged longitudinally, in 3 pairs. This will allow for an optimal hull shape. The arrangement in pairs allows the use of a center bulkhead. The tanks are placed forward in the hull, to balance the LCG with the required LCB. As much as possible of the LQ is arranged in the poop, to reduce the size of the house, this will reduce the windage of the vessel, and provide a better wind flow to the rotors.

5.2.2 Stability

The calculated GM, at this stage, = approx. 5.00 m

5.2.3 EEDI

The required EEDI, ref. (25) for the vessel, defined as a Gas tanker with 61 500 DWT: 5.14 g/DWT/nm

The minimum power required for the IMO bad weather scenario 2, ref. (26): 6440 kW

5.3 Ship design 80 000 t Cargo Capacity

5.3.1 Arrangement

The ship has 8 prismatic free form tanks, arranged longitudinally, in 4 pairs. This will allow for an optimal hull shape. The arrangement in pairs allows the use of a center bulkhead. The tanks are placed forward in the hull, to balance the LCG with the required LCB.

As much as possible of the LQ is arranged in the poop, to reduce the size of the house, this will reduce the windage of the vessel, and provide a better wind flow to the rotors.

5.3.2 Stability

The calculated GM, at this stage, = approx. 3.21 m

5.3.3 EEDI

The required EEDI, ref. (25) for the vessel, defined as a Gas tanker with 99 000 DWT: 4.13 g/DWT/nm

The minimum power required for the IMO bad weather scenario 2, ref. (26): 6 430 kW

5.4 Ship design 150 000 t Cargo Capacity

5.4.1 Arrangement

The ship has 27 vertical bilobe tanks arranged in 9 (3 x 3) cargo rooms. This will allow the for an optimal hull shape. This arrangement allows the use of 2 longitudinal bulkheads, in addition to the inner hull longitudinal bulkheads. The tanks are placed forward in the hull, to balance the LCG with the required LCB. These tanks will be further developed during the later design stages. As a starting point for the tank dimensions, the lobe diameter is the same as for the vertical cylindrical tanks from Table 27, and the volume is then adjusted to the required cargo capacity, and number of tanks.As much as possible of the LQ is arranged in the poop, to reduce the size of the house, this will reduce the windage of the vessel, and provide a better wind flow to the rotors.

5.4.2 Stability

The calculated GM, at this stage, = approx. 1.28 m

5.4.3 EEDI

The required EEDI, ref. (25) for the vessel, defined as a Gas tanker with 191 000 DWT: 3.06 g/DWT/nm

The minimum power required for the IMO bad weather scenario 2, ref. (26): 10 750 kW

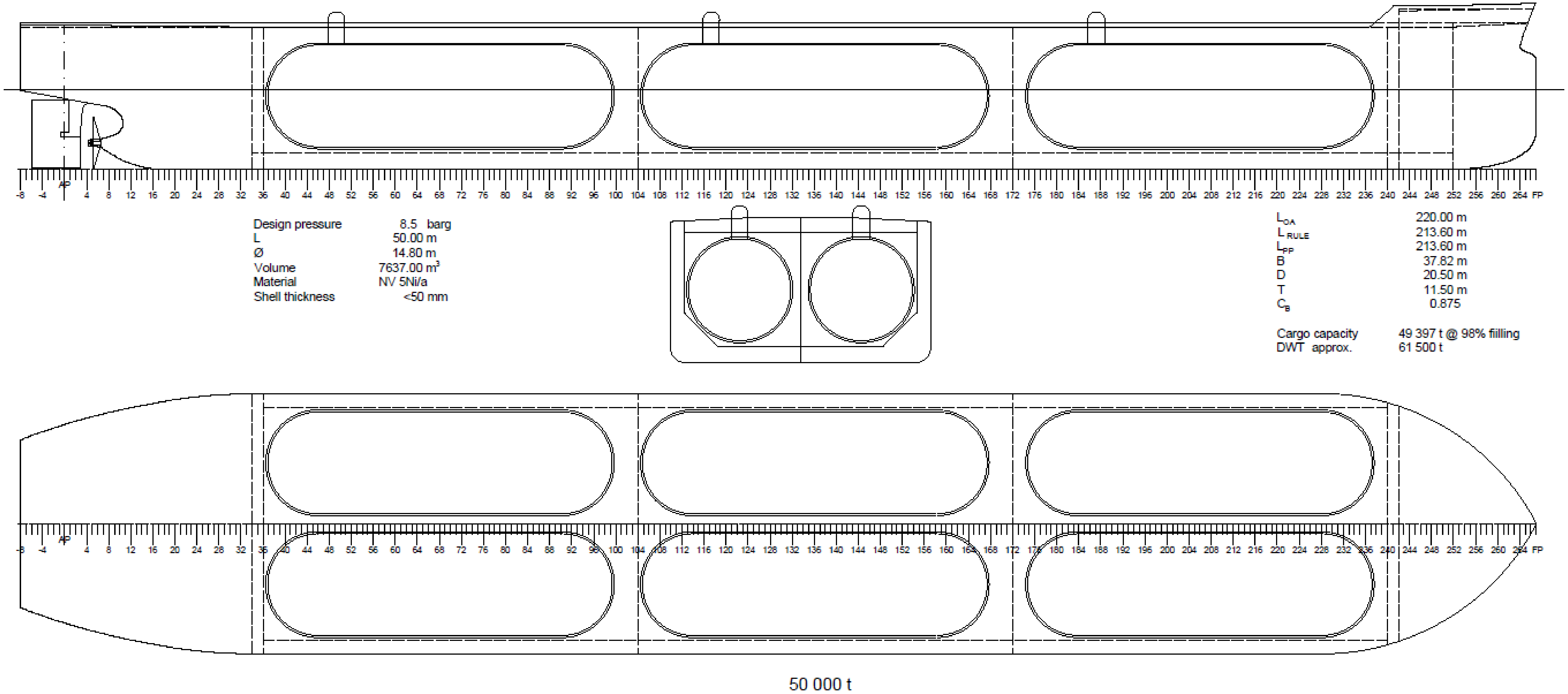


Figure 14 Cargo Capacity 50 000 t design

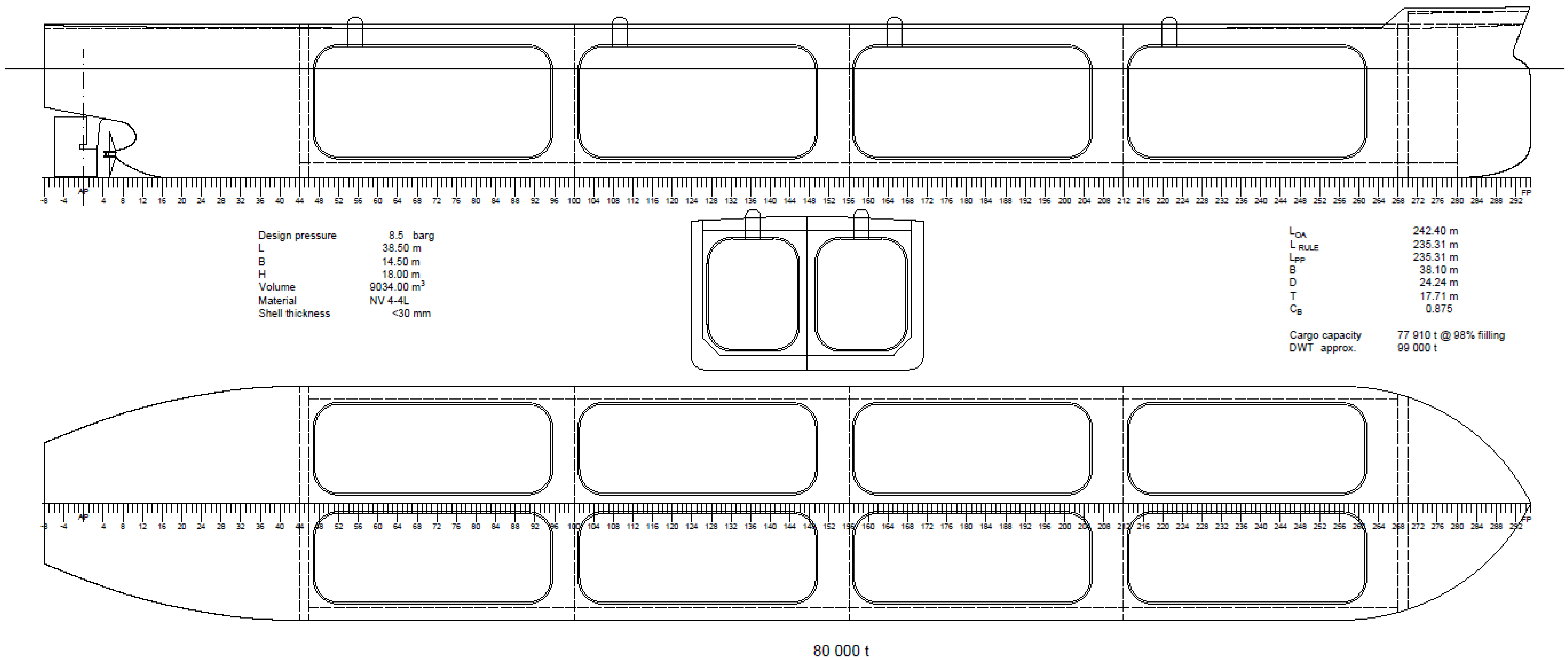


Figure 15 Cargo Capacity 80 000 t design

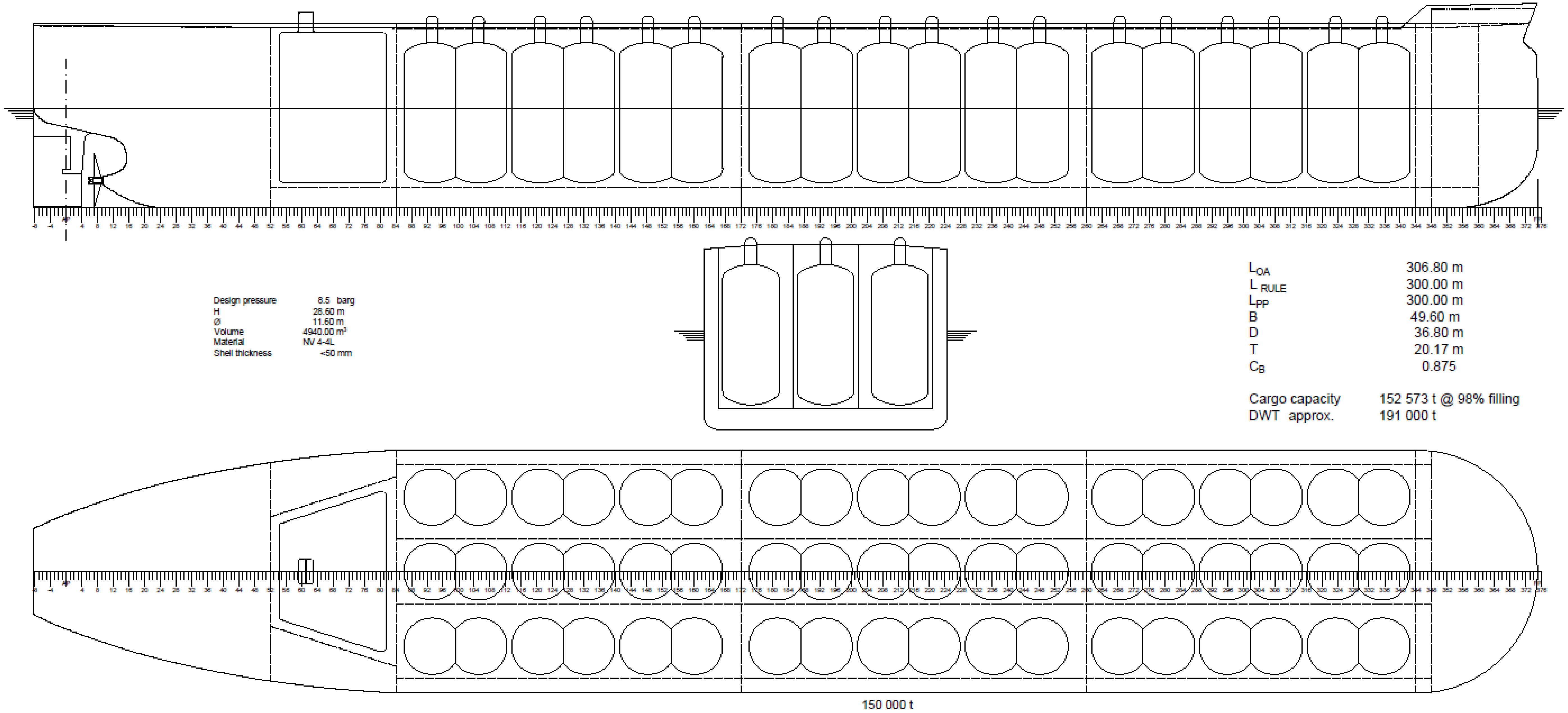


Figure 16 Cargo Capacity 150 000 t design

5.5 Project specific concepts from vendor

5.5.1 TGE

TGE has presented proposals for the CO_2 carriers (27). The proposed solutions are for 50 000 t, and 80 000 t capacity, as they regard the 150 000 t size as unviable, due to the number of tanks required.

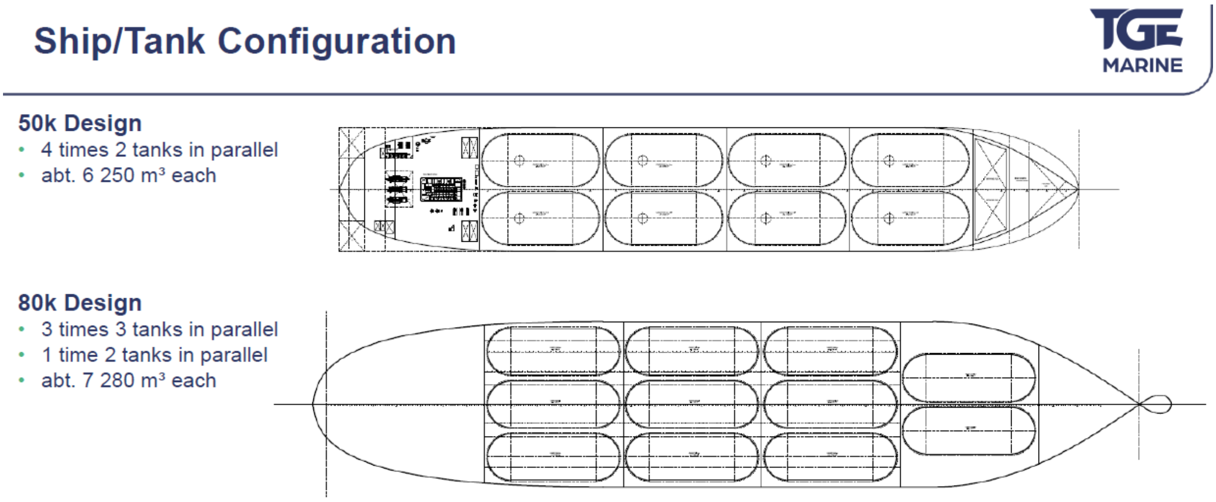


Figure 17 Tank arrangements proposed by TGE

For the 50 000 t vessel, the proposal is for an alternative with 8 tanks (l = 43.68 m; Ø = 14.30m, volume = 6 250 m^3), arranged longitudinally, in 4 pairs, ref. (27).

For the 80 000 t vessel, the proposal is for an alternative with 11 tanks (l = 50.00 m; Ø = 14.30 m, volume = 7 264.75 m^3), arranged in 3 rows of 3, and 1 row of 2, ref. (27).

5.5.2 Lattice Technology

Lattice Technology have presented an alternative for each of the ship sizes, using their LPV tanks, ref. (28).

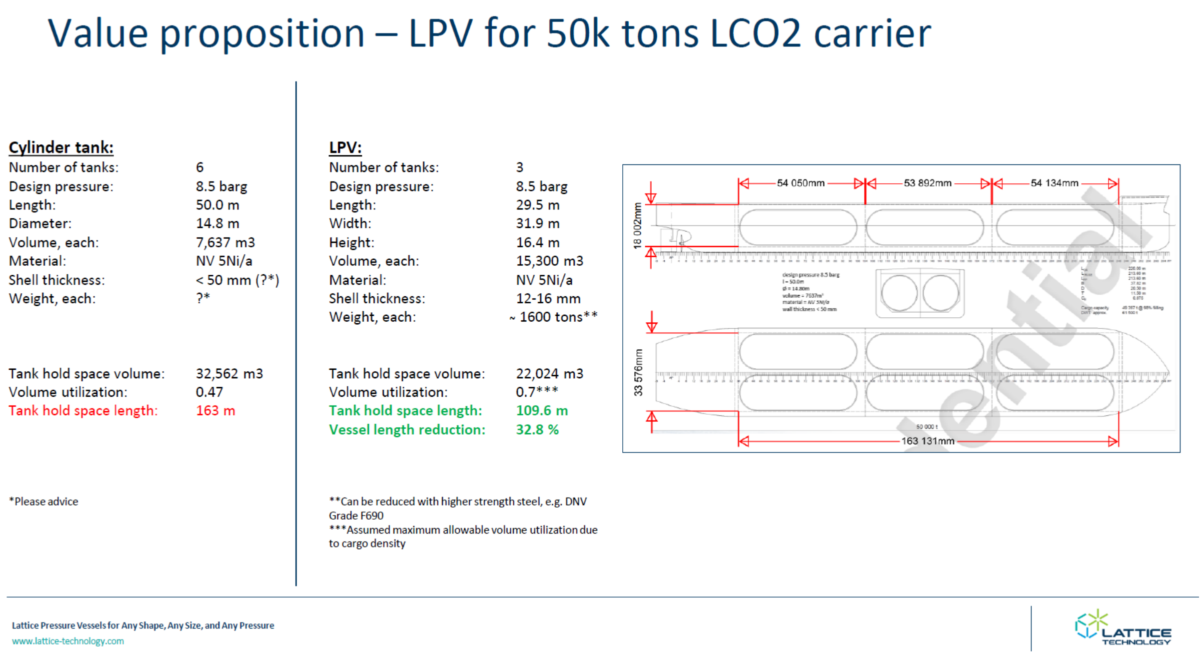


Figure 18 Tank arrangements proposed by Lattice Technology

- For the 50 000 t vessel, the proposal is for an alternative with 3 tanks (l = 29.5 m; B = 31.9 m, H = 16.4 m volume = 15 300 m3).
- For the 80 000 t vessel, the proposal is for an alternative with 4 tanks (l = 28.1 m; B = 31.9 m, H = 19.9 m volume = 17 750 m3).
- For the 150 000 t vessel, the proposal is for an alternative with 6 tanks (l = 17.8 m; B = 41.7 m, H = 30.2 m volume = 22 200 m3).

WP3 – FLOATING CO_2 TERMINALS

1 INTRODUCTION

There are many reasons why a floating terminal should be considered as an alternative to a "land-based terminal". One of the main and obvious reasons is that land area in major ports is often limited and expensive. If the terminal could utilize the sea area it may lead to reduced costs and area needed. Other reasons for designing a floating terminal in a ship transport chain may be:

- Deep water quays are limited, a floating terminal can provide deep water docking.
- A floating terminal will most probably be a dedicated dock and as such reach increased regularity.
- A floating terminal can be built and commissioned as a complete unit at a shipyard.
- A floating terminal can be redeployed.
- Floating terminals may include different facilities and have different locations. Here, a modular terminal system which can accommodate for different requirements is described.
- The possibility of CO_2 liquefaction in combination with the regasification of LNG from a FSRU (Floating Storage and Regasification Unit) has been explored. The simple idea is utilizing the advantage of "free" heat transfer between the two media, where one stream needs to be cooled down and the other being heated. This is a possible solution where a regasification unit is in the vicinity of a CO_2 capture site or hub.
- Different configurations and requirements for floating terminals on a general basis and by detailing two concepts A and B have been explored. Case A is set up to function as a terminal in the Stella Maris project, ref. (1). Case B is similar is designed to receive larger ships and will be situated in a remote location.

2 FUNCTIONAL ANALYSIS AND DESIGN BASIS FOR FLOATING TERMINALS

2.1 Introduction

Just as in other renewable energy sources and green technologies, such as wind and solar power systems, it should also be possible to locate CO_2 terminals for CCS logistics in a floating environment. Land-based CO_2 terminals for shipping are sanctioned and under construction and the option of floating terminals as an alternative are being investigated by several projects. Floating terminals can include different facilities and have different locations. Modular floating terminal systems which can accommodate different requirements have been developed. The requirements or functions discussed are:

- Operational area
- Buoyancy and strength elements
- Tanks for liquid CO_2
- Tanks for gaseous CO_2
- Tanks for ship bunkers (diesel, ammonia, hydrogen, LPG or LNG)
- Liquefaction module
- Mooring of ship (fenders, vacuum pads, bollards, outriggers or mooring dolphins)
- Loading arms/hoses or separate floating unit for loading and offloading

- Shore power or power generators with fuel tanks and possibly CO_2 capture
- CO_2 vapour return
- Ship supplies (fresh water, provisions, waste handling, etc)
- Position keeping of terminal (mooring or jack-up legs)
- Crew facilities
- Workshops / maintenance facilities
- Control room
- Material handling (cranes etc)
- Lifesaving and fire protection appliances
- Personnel transfer
- BOG treatment
- Cargo vent
- Modularity in design
- CO_2 terminal with integration or combination with FSRU

2.1.1 Justification of floating CO_2 terminals for shipping

There are several reasons why a floating terminal should be considered as an alternative to a land-based terminal. A few potential arguments are listed below:

- Land area in major ports is limited and expensive
- Deep water quays are limited, and a floating terminal can provide deeper water docking
- A floating terminal will most likely be a dedicated dock and provide better regularity
- A floating terminal can be built and commissioned as a complete unit at a shipyard
- A floating terminal can be redeployed
- In remote locations necessary infrastructure for a land-based terminal may not be present

2.1.2 Functions and Alternative Configurations to be Explored

Perhaps the simplest functions of a floating CO_2 terminal are a terminal that can import LCO_2 and intermediately store a certain quantity of it for subsequently exporting it. In addition, a CO_2 vapour return functionality should be included to balance volumes from the loading tanker and the LCO_2 terminal storage and in addition handle any BOG that may be produced. A CO_2 terminal for shipping will as a minimum further include docking facilities for the ships and loading/offloading facilities for the LCO_2. The basic functions of a CO_2 terminal are illustrated in Figure 19 below.

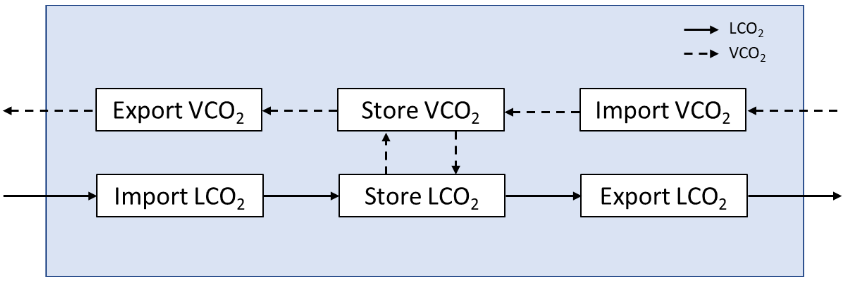


Figure 19 The basic functions of a floating CO_2 terminal

In a slightly more complex CO_2 terminal, one might consider having a liquefaction functionality so that the CO_2 terminal can handle both the BOG and the displacement volumes created by importing the LCO_2 and potentially also handle receipt of larger quantities of VCO_2 from a carbon capture plant on land. This added functionality is illustrated graphically in Figure 20 below.

In case the floating terminal is not supplied with electricity from shore or other sources, one would need to consider the energy source and if it is fossil fuels one could consider CO_2 capture onboard the floating facility. Such functionality could also be sized to capture carbon from any exhaust gas from an onshore facility. This would however be a very advanced added functionality and it is not considered further in this design basis or the WP3.

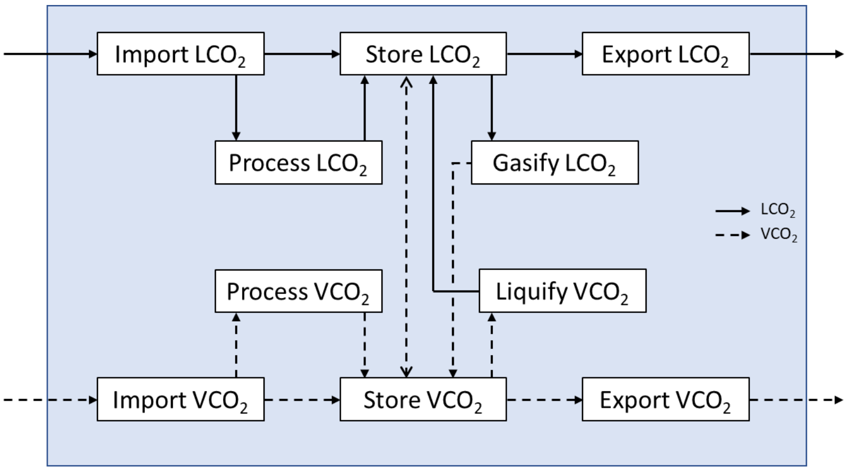


Figure 20 The floating CO_2 terminal with CO_2 liquefaction functionality.

2.2 Major and Minor Functions and Options

The following chapter will discuss, categorise, and select the various functions and options introduced in the bulleted list in the introduction in chapter 2.1.

2.2.1 Operational area

Designing the floating terminal without restrictions on selection of location would provide the best flexibility of the concept, it would however come with a cost. There are considerable savings in selecting a concept where choice of locations is limited to sheltered waters. Such savings may be related to the choice of mooring system, dimensioning of the hull structure related to wave loads, dimensioning of deck modules and necessary freeboard/protection with respect to green sea loads, tank scantlings due to accelerations etc. For this work it is decided that the unit shall be able to operate as a floating stationary unit in sheltered waters. With reference to DNV Rules, ref. (29) section 3.1.2, a maximum allowable significant wave height, H_s, will be calculated for each case.

Transit between yard and location(s) may require extra design considerations depending on the route and means of transportation either on a heavy lift vessel or by towing (the unit is not going to be self-propelled). As a preliminary assumption, transit condition is not considered dimensioning for any part of the design. This assumption should be revisited for an actual project where the building yard and possible transit routes and means of transport are known.

2.2.2 Buoyancy and strength elements

A floating structure or terminal can be built of various materials, such as concrete or steel. There are examples of LNG floating terminals in concrete, ref. (30), however for this work we have decided to look at steel constructions to create the buoyancy. The main argument for selecting a steel design, is the wide range of designers and shipyards available with competence within the field of floating marine steel structures. The steel construction will be designed and analysed in accordance with ref. (29). It is suggested as possible further work to develop a concrete design for comparison with the steel units.

2.2.3 Tanks for liquid CO_2

Different types of tanks for storage of liquified CO_2 are thoroughly discussed in WP2. Tank shapes are horizontal or vertical cylindrical, bilobe, trilobe, spherical and free form. Low cost, ease of production and technological maturity is considered as main selection parameters, resulting in a design with horizontal cylindrical tanks. Although hemispherical ends would allow for a larger tank diameter, ellipsoidal Korbbogen ends are selected as this design provides a better utilisation of the tank compartments.

Tank pressure and temperature is considered case specific but must always be kept within the limits applicable for liquefied CO_2. As a minimum to avoid forming of dry ice with ample margins, an operating pressure of 6 barg and at least a mechanical design pressure of 7 barg with a corresponding temperature of -50°C is needed. Current ship operations with liquefied CO_2 are done at operational pressures around 15 barg (mechanical design pressure 19 barg) and -30°C. Higher pressures are not considered for this work.

Tank sizes are maximised based on dimensioning criteria in the IGC Code, ref. (20), corresponding to a maximum plate thickness of 50 mm, in line with IACS UR W1, ref. (15). Selected material is case specific but shall not have a specified minimum yield stress exceeding 410 N/mm^2.

Tanks shall be installed below deck, insulated, and equipped with a dome protruding through the weather deck with all flanges, vents and couplings above deck level.

The total tank volume shall be 20% larger than the arriving ship to provide a buffer capacity. Typically, this will avoid having to shut down the capture process due to minor delays in the ship schedule. By increasing this percentage, improved regularity in the logistics chain may be achieved, but size and the construction costs of the floating terminal will increase.

2.2.4 Tanks for gaseous CO_2

Tanks for CO_2 in gas phase, would serve as buffer capacity between a pipeline and a liquefaction plant and for surplus displaced gas from storage tanks and ship cargo tanks. This buffer capacity will ensure more continuous running of the liquefaction plant.

The design pressure of the tank needs to match the pressure of the pipeline and the storage tanks, whichever is the highest.

The first compressor in the compressor train in the liquefaction plant will take suction from these tanks.

2.2.5 Tanks for ship bunkers (diesel, ammonia, hydrogen, LPG or LNG)

Where the export/import terminals or ship route are in an area with an established bunkering service for the required fuel type, there is no need to provide bunkering. However, remote locations or early implementation of new fuel types for the ship engines, such as ammonia, may require this functionality. Size of bunker tanks should be based on delivery schedules from the supplier, consumption, tank size of arriving CO_2 vessels and cost analysis. As a preliminary assumption, bunker tanks should be able to supply all arriving vessels with fuel within a 3-month period. For ammonia, this will be a very large tank, especially due to the lower energy density which is approximately 50% of LNG. It shall also be kept in mind that a treatment plant for operational flushes shall be provided. In addition, there are special requirements for venting from the pressure safety valves.

Selection of ship fuel type is case specific and may also change during the operation of the floating terminal.

2.2.6 Liquefaction module

The liquefaction module will consist of a compression train followed by a refrigeration plant. The capacity needs to match the actual requirements for the site in question. Factors to be considered are:

- Boil off gas rate
- Fraction arriving to the terminal in gas phase and incoming pressure
- Fraction arriving in liquid phase
- Displaced gas volumes during loading of the terminal
- Design pressure and temperature of the storage tanks
- Choice of refrigerant with respect to GWP
- Gas return from the ship being loaded

The type of refrigeration circuit shall be chosen with energy efficiency in mind. Possible turn down capacity is important as the inflow to the refrigeration plant is varying.

2.2.7 Mooring of ship (fenders, vacuum pads, bollards, outriggers or mooring dolphins)

Mooring of the ship could be directly to the floating terminal, to a separate installation or a combination of these. If the ship is moored to a separate installation such as single point mooring buoy or similar at a distance from the floating terminal, loading may be done by use of flexible loading hoses.

Conventional mooring by use of bollards and dolphins situated on the floating terminal, quays, piers, and outriggers normally require a minimum length of the berth exceeding that of the ship.

In order to develop a concept with a high degree of flexibility, an automated mooring system situated on the floating terminal will be used in the further work. This eliminates the need for other installations and reduces the needed length of the berth, hence the terminal length need not to be more than the ships parallel midship (where the ship sides are vertical and parallel to each other above the waterline). This solution will allow for use of flexible hoses or loading arms during loading of the ship.

2.2.8 Loading arms/hoses or separate floating unit for loading and offloading

Transfer of liquid CO_2 from the floating terminal to the ship may be done by use of loading arms or flexible hoses. Flexible hoses may be used in connection with a mooring/loading buoy, a jettyless transfer solution or where the ship is moored directly to the floating terminal. The loading arms require a connection with small relative movement between the ship and the floating terminal. These systems are described in detail in CO2LOS II - WP3 Logistics, Terminal and Port Technology, ref. (31).

This project will make use of loading arms in combination with automated mooring pads. This is considered to provide a fast and reliable loading sequence with an automated emergency release function and a minimum of potentially safety hazardous manual operations.

2.2.9 Shore power or power generators with fuel tanks and possibly CO_2 capture

The power requirement shall be based on the electrical load list for the terminal. It is suggested that each building block shall have a separate load list. Shore power is preferred if the CO_2 footprint of the shore power is less than for power from a generator. If this is not the case, a generator powered by LNG, green ammonia of green methanol is preferable.

In the case of LNG or methanol, CO_2 capture should be evaluated. It shall however be kept in mind that the capture process needs energy and that it can be assumed that the energy from the exhaust from the generator engine, is sufficient for catching 50% of the CO_2. If all shall be caught, more fuel is required.

This study will not evaluate the CO_2 capture solutions.

2.2.10 CO_2 vapour return

During loading of the tanker, displaced CO_2 gas and flash gas is sent ashore. Ideally, the displaced gas should match the volume taken from the intermediate storage, but according to experience there may be some extra flash gas. If a liquefaction module is installed, the excess displaced gas can be liquefied and sent to the storage tanks. If a liquefaction module is not installed, the surplus gas must be sent ashore.

This project is co funded by CLIMIT. CLIMIT Project No. 618181

2.2.11 Ship supplies (fresh water, provisions, waste handling, etc)

If the barge is installed in a remote location, and is equipped to supply bunkers, it should also have the capacity to supply fresh water and provisions, and to handle the ships waste. The capacity should be the same as for bunkers, with a preliminary assumption of 3 months capacity.

2.2.12 Position keeping of terminal (mooring or jack-up legs)

The floating terminal is by definition floating and not a jack-up or gravity-based structure resting on the sea bottom when in operation. A non-floating unit (except in transit) may be a feasible solution for special cases but are outside the scope of this work and not further evaluated here.

Mooring of a floating unit may be of a weathervaning type where the unit is free to rotate around the mooring point, or a spread moored solution where the unit is fixed to one position regardless of the direction of wind, waves and current. For ship-shaped units located in a harsh offshore environment, weathervaning is the preferred solution allowing the unit to meet the wind and waves with the bow, minimising the impact of environmental loads on the unit. This solution may normally not be combined with a side-by-side loading and require more advanced mooring equipment such as a turret or a mooring buoy.

In sheltered waters spread moored units is more common. This solution allows for side-by-side mooring and is the selected solution for this project.

2.2.13 Crew facilities

There are two scenarios for the installation of the barge.

It is installed in an existing harbour. The crew leave at the end of the day/ shift, and do not live on the barge. In this case, the crew facilities shall consist of:

Change room with showers and toilets

A mess room / canteen, with facilities for storing and heating food. Refrigerator, microwave oven, coffee machine etc.

It is installed in a remote location, so that it is necessary to live on the barge. In this case, the crew facilities shall consist of:

- Change room with showers and toilets
- A galley and mess, with provision storage for one month
- Recreation room
- Gym
- Laundry
- Cabins, at a minimum in accordance with the Maritime Labour Convention 2006 / Title 3 - Accommodation recreational facilities, food and catering
- Hospital accommodation in accordance with MLC 2006, or the competent local authority
- Prayer room

2.2.14 Workshops / maintenance facilities

Electrical and mechanical workshops shall be provided for maintenance work.

2.2.15 Control room

In all instances, a control room shall be provided. This project does not envisage the use of a remote controlled, unmanned barge. All activities and operations shall be controlled from this room. These activities include:

- Cargo operations
- Ballast operations
- Mooring operations
- Bunkering operations
- Communications
- Fire & Safety surveillance and operations

Operator stations and large screen displays shall give the operators sufficient and effective information about relevant parameters, activities, modes, alarms etc.

2.2.16 Material handling (cranes etc)

Material handling systems are needed to handle the maintenance requirements of the installation. This will include:

- For the liquefaction plant:
- Crane coverage of the plant, to dismantle the components for maintenance.
- A laydown area for the components.
- A means of transporting components to/from a laydown area at the gunwale. Forklift and /or hand pallet trucks.
- Crane coverage of the gunwale laydown area, for loading/ offloading.
- For the cargo tanks:
- Equipment to remove pumps, valves etc. from the tanks for maintenance. Removeable davit.
- Transportation of components to workshops or gunwale laydown area. Forklift and /or hand pallet trucks.
- For the provisions, supplies:
- Forklift and /or hand pallet trucks.

2.2.17 Lifesaving appliances

The unit will be classified as a manned barge and shall be outfitted with lifesaving appliances in accordance with SOLAS Ch III, ref (22) and the IGC Code, ref. (32), fulfilling the requirements for gas carriers. This will include:

- Personal life-saving appliances in accordance with Part B. Section I Regulation 7, and Section III Regulation 32.

- Survival craft and rescue (MOB) boats, in accordance with Part B. Section III regulation 31. The lifeboats shall be used as rescue boats, in accordance with Reg. 31.2.
- Line-throwing appliance, in accordance with Part B. Section I Regulation 18.

2.2.18 Fire protection appliances

The unit will be classified as a manned barge and shall be outfitted in accordance with SOLAS Ch II, ref (22) and the IGC Code, ref. (20), fulfilling the requirements for gas carriers. CO_2 is not flammable or explosive, so there is no great fire risk due to the cargo. The normal requirements for cargo ships shall apply for:

- Fire detection and alarm.
- Fire containment by thermal and structural boundaries.
- Firefighting.
- Means of escape.

If the barge is to have the capability to provide bunkers for visiting ships, then the appropriate fire protection measures need to be provided. These will vary according to the type of bunkers provided.

2.2.19 Personnel transfer

Depending on the location, there are several possible methods for transferring personnel to and from the barge. If it is installed in an existing harbour, it may be possible to use a gangway to shore. If possible, this is the least expensive option. Alternatively, transfer by boat is an option. Transfer by helicopter is not seen as realistic in this scenario. If it is installed in a remote location, the alternatives are transport by boat or helicopter. Transfer by boat will be the least expensive and is possible with a max wave height of approximate 2.5 m. Transfer by helicopter will only be relevant if the distance to the installation is so long that the travel time by boat is unacceptable. The use of helicopters for normal personnel transfer will require the installation of a helideck in accordance with CAP 437 Ch.9.1. ref. (33). If a boat is used for normal personnel transfer, a helicopter landing/winching area shall be provided for emergency use, in accordance with CAP 437 Ch.9.2. In this study the solution will be either by gangway or based on boat transfer.

2.2.20 BOG treatment

Reference is made to Ch 2.2.6, where the liquefaction plant is discussed. According to the rules, ref. (16), the pressure and temperature can be maintained using the following methods, either alone or in combination.

- Energy consumption by ship
- Re-liquefaction
- Thermal oxidation
- Pressure accumulation

For CO_2 only re-liquefaction and pressure accumulation is feasible. The choice of method will depend on the size of the terminal, the inflow and the frequency of ship loading. However as illustrated in

Figure 20, the BOG and other surplus gas can also be exported from the terminal to the shore facility that provides the liquid CO_2.

2.2.21 Cargo vent

A high carbon dioxide (CO_2) gas concentration can cause suffocation and the IGC Code, ref. (20), chapter 19 classifies CO_2 as an “asphyxiant”. However, CO_2 could more correctly be categorized as “toxic” and many countries provide exposure limits. In Norway the limit is 5000 ppm, or 0.5%, ref. (34). As the carbon dioxide concentration in the ambient air we are breathing increases, lower quantities of carbon dioxide leave the blood stream. Consequently, the concentration of carbon dioxide in the blood and tissues increases, the pH of the blood falls, to which the human body is extremely sensitive. Elevated blood and tissue levels of carbon dioxide are termed hypercapnia or hypercarbia. This effect is called intoxication. Carbon dioxide intoxication is entirely independent of the effects of oxygen deficiency (i.e., asphyxiation), therefore the oxygen content in the air is not an effective indication of the danger of intoxication. Appropriate warning signs shall be placed at the entrance to confined areas where high concentrations of carbon dioxide gas can accumulate. In addition, it would be required to have gas sensors monitoring the gas concentration levels.

During various operation modes of the terminal, it may be necessary to release larger quantities of CO_2 and a properly designed and located cargo vent mast would therefore be required.

2.2.22 Modularity in Design

With the multiple functionalities mentioned above, one would also investigate if modularity in the design could offer benefits. This is further treated in chapter 3.

2.2.23 CO_2 liquefaction terminal with integration or combination with FSRU

A floating terminal that imports and liquifies CO_2 gas from shore requires energy to cool down the compressed gas in several stages. In the operation of FSRUs, the LNG is regasified from its liquid state at –160 to -170 °C, before it is sent onshore to the consumers. To vaporise the LNG, heat is required. The normal way of vaporizing LNG at an FSRU installation is to either use the seawater around the FSRU or using the ambient air as the heating medium. This results in cold air around the FSRU or colder water around the FSRU. The first option requires huge fans, while the latter option can be problematic for life in sea as it reduces the water temperature, especially in shallow waters along the coastlines which are the likely locations of FSRUs. Strict environmental regulations must be followed for the cold seawater discharge. A third option used is to heat the LNG from its cryogenic state by a closed loop system in which a freshwater/glycol mixture is circulated and pre-heated by steam from the ships’ boilers. This third option requires energy and would again give another source of emissions. An alternative way of vaporizing the LNG, which is proposed here, is to combine the FSRU facility with a liquefaction plant of gaseous CO_2.

Since regasification of LNG requires heat and the liquefaction of CO_2 requires cooling it should be theoretically possible to benefit somewhat from heat transfer between the two media. The functions of a terminal that combines a CO_2 terminal and a regasification terminal is depicted in Figure 21 below indicating the heat transfer with a red line between the liquefaction of VCO_2 and vaporization of the LNG.

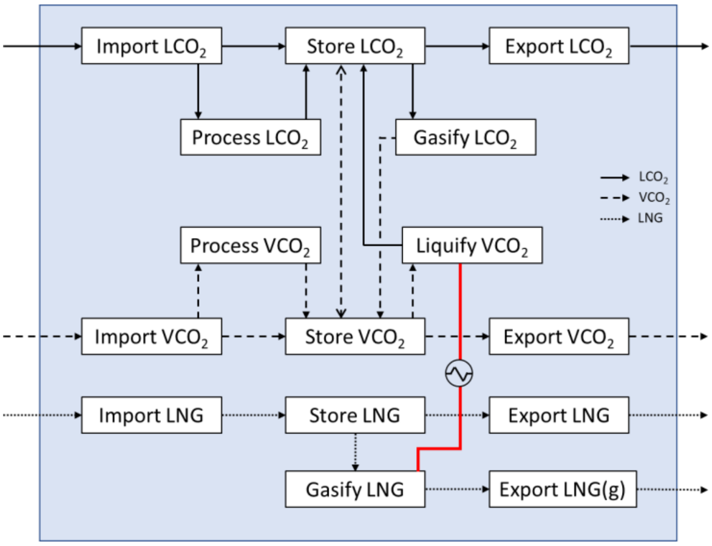


Figure 21 The floating CO_2 terminal with integrated CO_2 liquefaction and LNG regasification functionality

If the terminal is installed in the vicinity of a FSRU, part of the heat needed for regasification could be taken from the CO_2 gas stream. To vaporize 0.7 tonnes of liquid methane at 0.5 barg, 1 tonnes of CO_2 at 7 barg can be liquified. An LNG heat-exchanger with the necessary instrumentation needs to be installed. It is very important to have a tight follow-up of the CO_2 temperature out of the heat exchanger to avoid formation of dry ice.

More detailed exemplification of potential advantages and a design of such integrated functionalities are investigated and is presented separately in chapter 4.

2.3 Terminal configurations and specifications

In Chapter 1 several functions of a generic CO_2 terminal were presented, argued and selected for the further design as part of WP3 terminal design cases. These are summarized in Table 29 below. This Chapter further defines the more specific design bases for configuration A and Configuration B that will be designed in the further work.

Table 29 Generic Summary of functionalities of a floating CO_2 terminal

Item	Functionality	Design
1	Operational area	Sheltered areas (max allowable Hs to be calculated)
2	Buoyancy and strength elements	Steel construction
3	Tanks for liquid CO_2	Yes. Cylindrical horizontal tanks.

Item	Functionality	Design
4	Tanks for gaseous CO_2	Yes. Cylindrical horizontal tanks. This is for lower pressure and is usually the headspace of the tanks for liquid CO_2. However, the first knock out drum of the liquefaction plant will also act as buffer for the incoming CO_2 from a capture plant.
5	Tanks for dense phase CO_2	Cylindrical vertical tank. Forms a part of the conditioning for high pressure or dense phase CO_2 from pipeline.
6	Tanks for ship bunkers	Yes. Cylindrical horizontal tanks.
7	Liquefaction module	Yes (sizing according to further specifications)
8	Mooring of ships	One ship moored directly to terminal with vacuum pads
9	Loading arms/hoses	Loading arms
10	Shore power or power generators	Case specific selection
11	CO_2 vapour return	Yes
12	Ship supplies	Yes (supplies and capacities according to further specifications)
13	Position keeping of terminal	Spread moored or moored to jetty/quay
14	Crew facilities	Yes (facilities according to further case specifications)
15	Workshops /maintenance facilities	Yes (facilities according to further case specifications)
16	Control room	Yes
17	Material handling	Yes
18	Lifesavings appliances	Yes
19	Fire protection appliances	Yes
20	Personnel transfer	By gangway or by boat
21	BOG treatment	Yes, by liquefaction module or CO_2 vapour return
22	Cargo vent	Yes
23	Modularity in design	Yes
24	Integration with FSRU	This is a separate case handled by doc: 21206-Z-RA-100-016

2.3.1 Terminal Configuration Case A Specification

It has been decided that the Case A specifications and functions are equal to the Stella Maris CCS ref. (1). The Stella Maris Project has the following main elements.

Floating CO_2 Collection, Storage and Offloading hub (CCSO) located in the proximity of a central cluster of industry, which will allow for the reception and further conditioning of various grades and stated of CO_2. The CCSO is moored at jetty with personnel gangway access.

Shuttle tankers with a capacity of 50.000 m3 of liquid CO_2 under low pressure, making the total amount of CO_2 injected up to 10 million tons per year. This number is equivalent to 20% of Norway's carbon dioxide emissions.

The CCSO hub is designed to receive and process:

- Low-pressure gas from pipelines
- High pressure or dense phase CO_2 from pipelines
- Medium- & Low-pressure liquid from road, rail, ships or barges
- Various qualities with different levels of impurity
- A storage of 50-80k m^3 liquid CO_2, with focus on high end 80k m3
- Designed for shore power
- The LCO_2 is stored at 6.5 barg and - 47 °C

In summary the design information and parameters listed in Table 30 will be used for the Case A Configuration version of the terminal which is intended to mimic the Stella Maris CCSO floating terminal.

Table 30 Summary of functionalities, design information and parameters of CO2LOSIII version of the Stella Maris Terminal

Item	Functionality	Design
1	Operational area	In a fjord or along a coastline in protected and densely populated areas (max allowable Hs to be calculated)
2	Buoyancy and strength elements	Steel construction
3	Tanks for liquid CO_2	Total capacity is 60.000-80.000 m^3. The tanks are made from NV 5Ni/a with a max thickness of 50 mm and a mechanical design pressure of 8 barg
4	Tanks for gaseous CO_2	Yes
5	Tanks for ship bunkers	No
6	Liquefaction module	Yes, with output capacity of 1000 m^3/h liquid CO_2
7	Mooring of ships	One ship moored directly to terminal. Mooring is with vacuum pads
8	Loading arms/hoses	Loading arms
9	Shore power or power generators	Shore power to Terminal and moored tanker
10	CO_2 vapour return	Yes
11	Ship supplies	Yes
12	Position keeping of terminal	Moored directly to a jetty
13	Crew facilities	Yes (facilities for dayworkers)
14	Workshops /maintenance facilities	Yes
15	Control room	Yes
16	Material handling	Yes
17	Lifesavings appliances	Yes
18	Fire protection appliances	Yes
19	Personnel transfer	Access with gangway from jetty
20	BOG treatment	Yes, with reliquification

Item	Functionality	Design
21	Cargo vent	Yes
22	Modularity in design	Scalable design
23	Integration with FSRU	No. Separate case handled by doc: 21206-Z-RA-100-016

2.3.2 Terminal Configuration Case B Specification

The terminal configuration B is a fictitious specification with the following main specification and definition:

- Located in remote area
- Tanker size able to receive up to 150,000 m^3 of liquid CO_2
- Terminal storage size 20% above largest ship: 180.000 m3 of liquid CO_2
- Able to provide ship supplies
- Ship bunkering facilities (Ammonia)
- BOG treatment through reliquification
- Selfsustained with power (no power to ship)
- Crew facilities
- The LCO_2 is stored at 6.5 barg and - 47 °C
- Liquefaction plant output capacity of 1000 m^3/h with liquid CO_2

The further specifications and the above is summarized in Table 31 below.

Table 31 Summary of functionalities, design information and parameters of the Terminal Configuration B

Item	Functionality	Design
1	Operational area	Worldwide in remote area (max allowable Hs to be calculated)
2	Buoyancy and strength elements	Steel construction
3	Tanks for liquid CO_2	180.000 m^3. The tanks are made from NV 5Ni/a with a max thickness of 50 mm and a mechanical design pressure of 8 barg.
4	Tanks for gaseous CO_2	Yes
5	Tanks for ship bunkers	Yes (Ammonia)
6	Liquefaction module	Yes, with output capacity of 1000 m^3/h liquid CO_2
7	Mooring of ships	One ship moored directly to terminal. Mooring is with vacuum pads
8	Loading arms/hoses	Loading arms
9	Shore power or power generators	Selfsustained with Power. No power supply to loading ship.
10	CO_2 vapour return	Yes
11	Ship supplies	Yes
12	Position keeping of terminal	Spread moored
13	Crew facilities	Yes, full time

Item	Functionality	Design
14	Workshops /maintenance facilities	Yes
15	Control room	Yes
16	Material handling	Yes
17	Lifesavings appliances	Yes
18	Fire protection appliances	Yes
19	Personnel transfer	Access with boat
20	BOG treatment	Yes with reliquification
21	Cargo vent	Yes
22	Modularity in design	Modular and Scalable design
23	Integration with FSRU	No. Separate case handled by doc: 21206-Z-RA-100-016

3 MODULARIZATION CONCEPT PRINCIPLE

3.1 Modularity Philosophy

As described in chapter 2.1.2, the basic functions assumed for a floating CO_2 terminal are import, storage and export of CO_2, assuming import, export or both will be by ship.

Modularisation of the CO_2 storage is an important part of the design philosophy of the terminals. Sizing of CO_2 storage is closely connected to the size of the ships. As a minimum the terminal must have sufficient storage capacity to receive or deliver a full ship load of liquid CO_2 without causing unnecessary delays to the ships schedule. Any additional buffer capacity to avoid shutting down receipt from a capture facility or delivery to an injection facility due to late ship arrivals etc, should be evaluated for each project.

Modularisation will also be applied to other functionalities listed in chapter 2.3, Table 29, such as liquefaction, conditioning of dense phase CO_2 and onboard power generation, if installed. Sizing of these functions are linked to the maximum volume of CO_2 handled over the terminal rather than the ship size.

A modular approach to these items is expected to reduce engineering costs and improve delivery time for a project. Modularity in the design phase is the base case. Modularity in the installation phase will only be evaluated if the terminal is too large for transport from the construction site. Modularization will also allow for improved turn-down capacity.

Other functions such as mooring, loading arms, crew facilities, etc are not modularised and hence not further described in this chapter.

3.1.1 Storage tanks modularity

According to chapter 2.2, the terminal shall be constructed as a steel hull with independent horizontal cylindrical CO_2 storage tanks with all necessary equipment (pumps, vents etc). The tanks shall be placed in cargo holds below deck. Typically, a single module will consist of one CO_2 tank oriented longitudinally in the hull section with a double bottom and double sides around the perimeter of the terminal for ballast water, ref. Figure 22. In general, the tank will be maximised in diameter according to the Rules, ref. (20) with a max plate thickness of 50 mm. The surrounding structure will be fitted around the cargo tank and form the hull of the terminal. Clearings between the tank and the hull structure will at least be according to requirements in ref. (20).

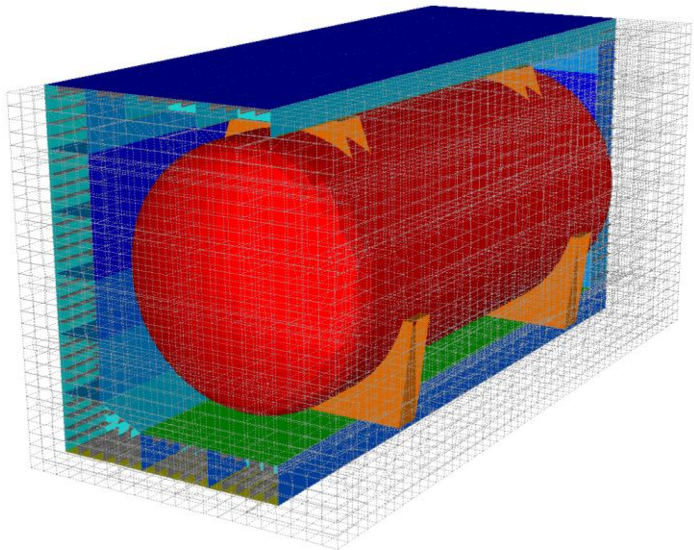


Figure 22 Basic storage tank and terminal hull module

If the need for storage capacity exceeds that of one cargo tank, more modules will be added. The number of modules and how to best arrange them will depend on several factors such as:

- Sufficient length relative to the ship for safe mooring by use of vacuum pads
- Other use of part of the terminals hull than cargo, such as tanks for bunker supply
- Longitudinal strength and stability, avoid excessively long and slender designs
- Space limitations at the location, could be both length, breadth, and draft restrictions
- Examples of how module arrangements may be solved are given in Appendix 1: General arrangement of cases A and B as shown in Figure 23.

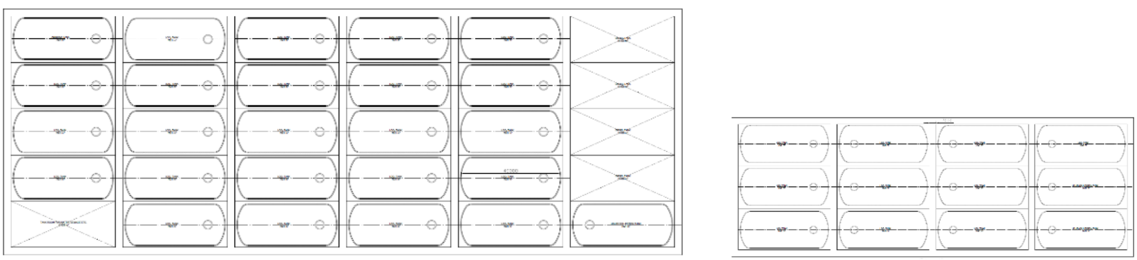


Figure 23 Extract from Appendix 1: General arrangement of cases A and B, showing Case B and Case A arrangements

3.1.2 Liquefaction plant modularity

The liquefaction plant transforms gaseous CO_2, typically from a capture plant, to liquid low-pressure CO_2.

The plants modularity is in general solved by adding standard size compressors and intercoolers as the volume of CO_2 increases. However, the number of knock-out drums are not intended to increase, only the size. The knock-out drums are sized based on residence time for the largest flow. This modularization concept will also improve the turn down capacity as at low incoming flow only the A-train can be online and run at its optimal operating point.

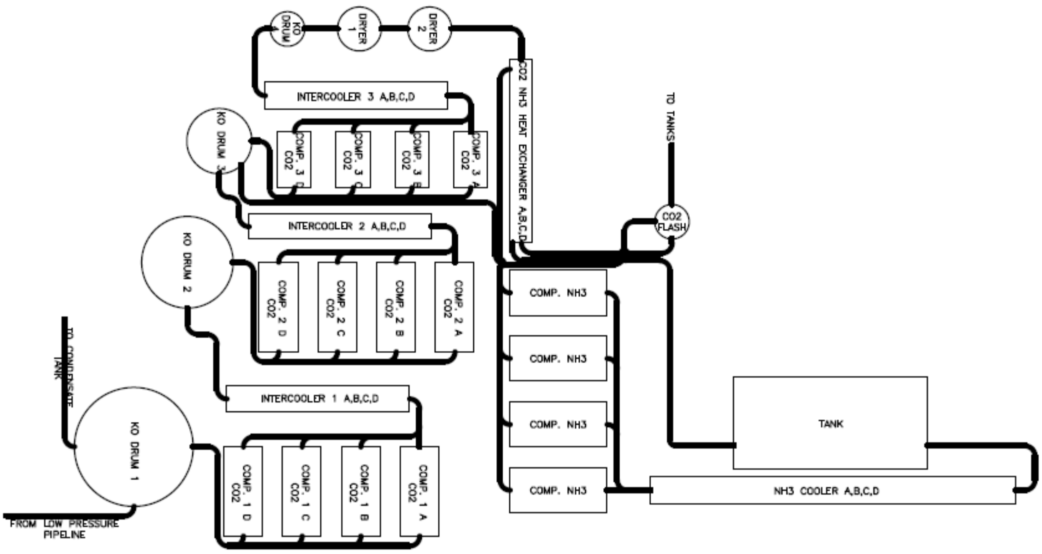


Figure 24 Extract from Appendix 1: General arrangement of cases A and B, showing Case B liquefaction plant

3.1.3 High pressure plant modularity

The high-pressure plant transforms dense phase CO_2, typically from a pipeline, to liquid low-pressure CO_2 suitable for ship transport.

The plants modularity is in general solved by adding standard size compressors and intercoolers as the volume of CO_2 increases. However, the number of flash drums are not intended to increase, only the size.

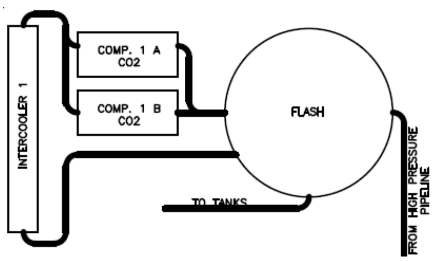


Figure 25 Extract from Appendix 1: General arrangement of cases A and B, showing Case B high pressure plant

3.1.4 Power plant modularity

The main electricity consumers are the process modules, if installed. The plant's modularity is solved by adding standard size generators as the estimated power consumption increases.

3.1.5 Making a design by use of modularity

When performing a design by use of modularity for the items described in chapter 3.1.1 to 3.1.4, a number of parameters should be known:

Table 32 Module size/capacity

Parameter	Module size/capacity
Liquid CO_2 storage tank capacity (one tank)	W [t]
Module length (one cargo tank inside)	X [m]
Capacity of standard liquefaction compressors and intercoolers	Y [t/hour]
Capacity of standard high pressure plant compressors and intercoolers	Z [t/hour]

Table 33 Sizing parameters

Parameter	Value
Ship cargo capacity x buffer factor	A [t]
Ship length	B [m]
CO_2 stream (max/hour)	C [t/hour]

The initial design should then satisfy the following formulas:

$n_1 \geq \frac{A}{W}$ n_1 = number of liquid CO_2 storage tanks (integer)

$n_2 \geq \frac{C}{Y}$ n_2 = number of standard liquefaction compressors and intercoolers (integer)

$n_3 \geq \frac{C}{Z}$ n_3 = number of standard high pressure plant compressors (integer)

$n_4 \geq \frac{2B}{3X}$ n_4 = number of modules arranged longitudinally (integer)

The initial design achieved by utilising the formulas above may need to be revisited when the items listed in chapter 3.1.1 have been evaluated and properly accounted for.

4 FSRU INTEGRATION

4.1 Liquefaction CO_2 by evaporation of LNG

Where an FSRU is in the vicinity of a CO_2 terminal, it may be feasible to utilize the cold energy released during the vaporization of LNG to liquefy CO_2 instead of using seawater or air as heat source. This process will be more environmentally friendly in addition to saving energy by avoiding both the refrigeration unit and the large air-heater for the evaporation of the LNG.

The saving potential is in the range of 35–40 kW/t CO_2 for the CO_2 liquefaction. For the LNG evaporator the saving is around 5-10 kW/t LNG based on the fan of the large air-heater.

There are three possible cases where liquefaction of CO_2 is needed:

- Liquefaction of BOG from the storage tanks at the terminal
- Liquefaction of gaseous CO_2 from a low-pressure pipeline or from a nearby CO_2 capture plant
- Liquefaction of gaseous CO_2 from a high-pressure pipeline

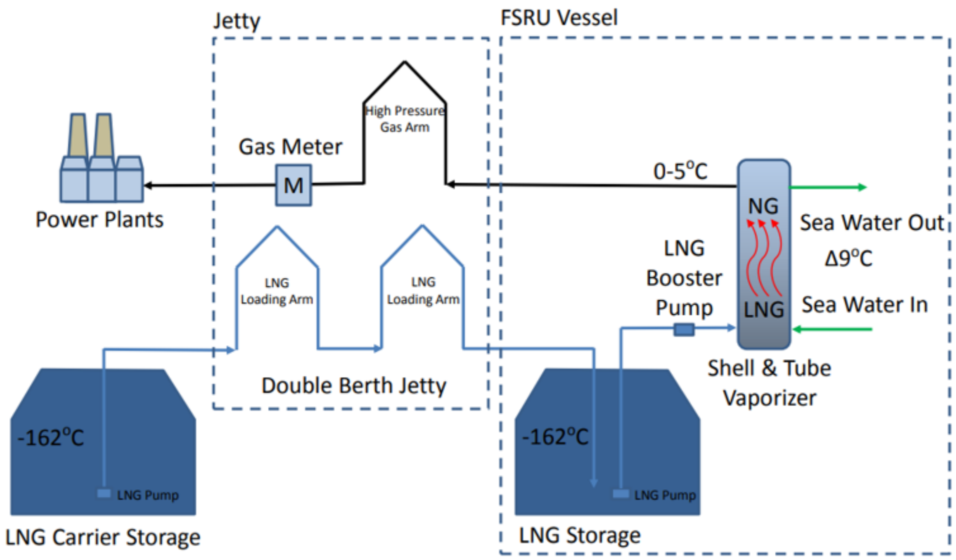


Figure 26 Typical interface between LNG carrier, FSRU and power plant, ref. (35)

In the case shown in Figure 26, a booster pump is pressurizing the LNG to 90 barg. In this case there is no CO_2 capture and liquefaction.

Possible integration between and FSRU and a capture plant can be seen in Figure 27.

The integration can be between an incoming pipeline with pressure above 80 barg and the FSRU. In this case the cooling capacity of the LNG will be used to cool the flash gas downstream the separator.

The actual flow of CO_2 is not known in either of the cases mentioned above:

- For case 1, the size and design of the storage facility is not known.

- For case 2, the capacity and pressure from the pipeline or capture plant are not known.
- For case 3, the capacity and pressure from the pipeline are not known.

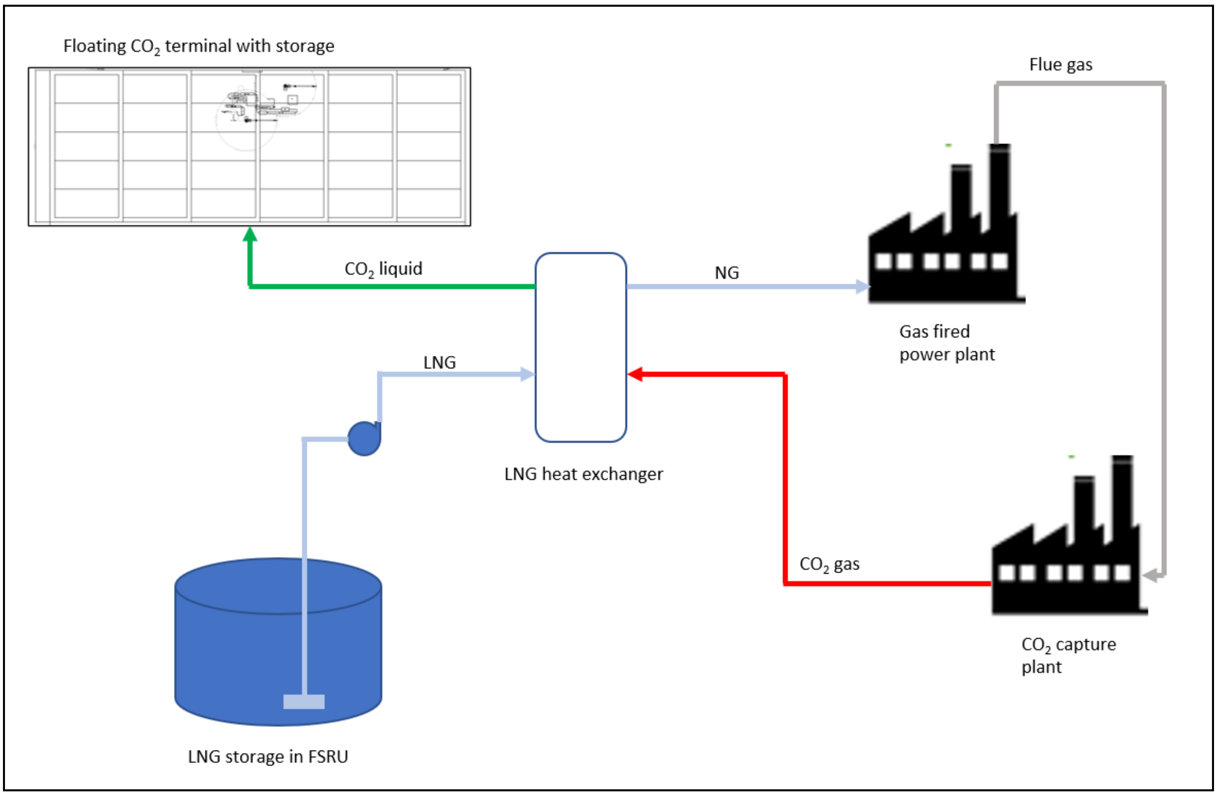


Figure 27 Sketch showing possible integration between an FSRU and a floating CO_2 terminal

5 PROCESS AND UTILITY MODULES

Below is an overview over the different functions and modules which may be part of the floating terminal.

Please note that not all these functions are related to process and utilities. The floating terminal is planned to be moored in sheltered waters and to be connected to a CO_2 hub via pipeline.

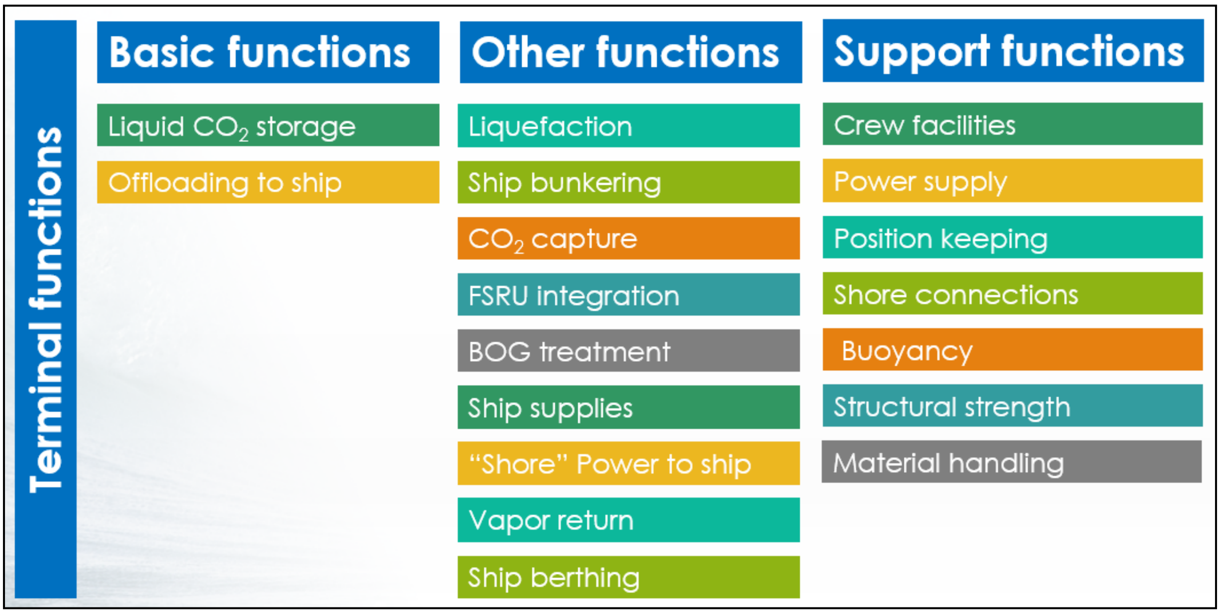


Figure 28 Overview over the different functions which may be included in a floating terminal

Process:

- Cargo system including storage.
- Gas return to ship.
- Liquid headers.
- Liquefaction including BOG re-liquefaction.
- Floating Storage and Re-gasification Unit (FSRU) integration.
- CO_2 capture

Utilities:

- Power supply, from shore or generator.
- Instrument air & service air.
- Offloading to ship.
- Seawater cooling system.
- Freshwater cooling system.
- Ballast system.
- Nitrogen system.
- Bunkering system.
- Firewater system.
- Waste handling.

5.1 Storage module - cargo system, offloading pumps, and ballasting

The storage tanks used for the liquid CO_2 storage, will need to be equipped with two deep-well type pumps each for offloading to ship. This system shall be designed according to the IGC code, ref. (20).

Headers for incoming liquid CO_2 either from shore or from the liquefaction plant and an unloading header for liquid CO_2 to ship, shall be installed.

Based on the design basis, given in chapter 2.2.3, the storage tanks will be cylindrical C-tanks with Korbbogen heads. The size of the separate tanks shall be maximized based on the rules. The tanks used in this report have a volume of 7 821 m^3. The total size of the storage facility will be based on the size of the ships, the filling rate of the storage and the mean time between ship arrivals. The storage facility may therefore consist of several storage modules.

The smallest standalone storage module will consist of at least two tanks with offloading facility integrated into a floating terminal. Connections from the loading arms to the ship loading manifold shall be compatible with the SIGTTO recommendations, ref. (36), for loading and offloading. Each tank should preferably be equipped with a suction well.

Each tank will be equipped with a dome where the cargo piping, pumps, necessary instrumentation and pressure safety valves (PSV) are installed. Two (2) PSVs are required for each tank according to the IGC code, ref. (20).

A preliminary sizing of the safety valves indicates that valves with Q orifice is needed. The estimated flow is 49 000 Nm^3/h.

Estimated BOG formation rate based on the tank size and 0.3 m insulation, is 125 kg/h. The calculation is based on a design pressure of 8.0 barg and a void space temperature of 20°C.

The vent line from these PSVs shall be short and free from obstructions, ref. (16) and IGC 17.21.3, ref. (20). It is not required to comply with IGC 8.2.10 and DNV Sc 8 [2.1.10] ref. (16), regarding the location of outlets of the vent lines at 6 m above Weather deck, working areas and walkways.

The capacity of the cargo pumps will be 300 m^3/h each achieving a total offloading capacity of 600 m^3/h per storage tank.

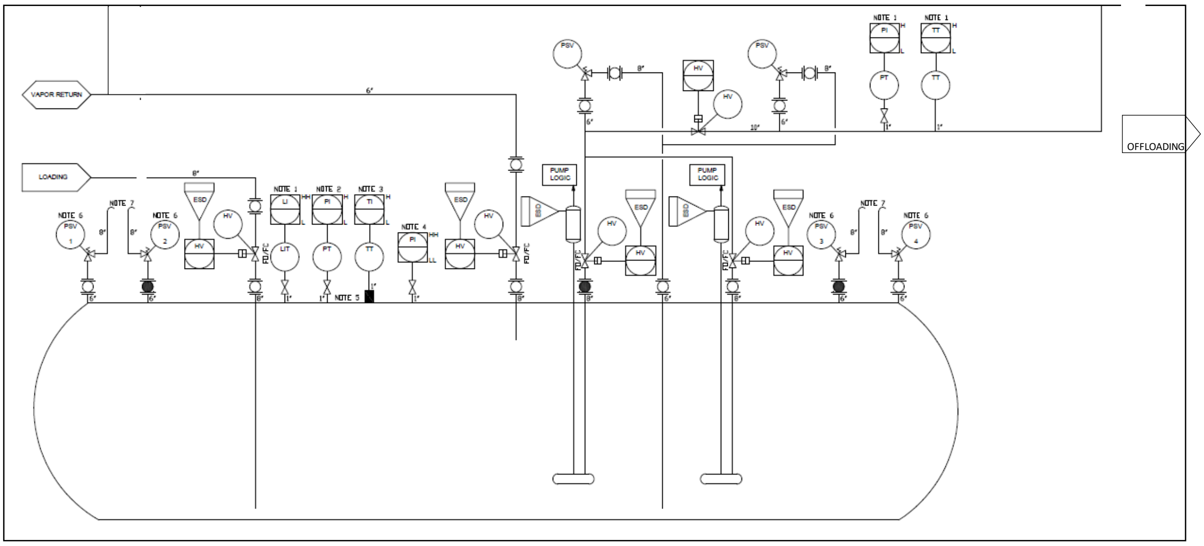


Figure 29 Typical offloading system and tank instrumentation

Each tank shall be equipped for inspection. This requires each tank to be fitted with a manhole, and a connection for dry air, to facilitate gas freeing.

The floating terminal will also need a ballast system to be able to compensate for the quantity of CO_2 liquid being offloaded to a ship.

5.1.1 Ballast system

A ballast system is required for the floating terminal.

Included in the ballast system are ballast pumps, and ejectors for stripping of ballast tanks.

As this terminal will stay at the same location a ballast management system is not required. The ballast system shall be able to be filled by pumping.

5.2 Tank for gaseous CO_2

The design pressure shall be sufficient to handle the incoming pressure from the pipeline. This may vary from case to case. The tank will serve as a buffer tank between the liquefaction plant and the pipeline. The inlet to the liquefaction plant will depend on the pipeline pressure.

For long distance pipeline transport of CO_2, dense phase is considered the most economic and is the state of the art for long distance transport. It is important to avoid phase changes, ref. (37), and therefore the pressure is kept above the critical pressure.

For shorter transport such as from a nearby CO_2 capture plant, the pressure may vary, depending on the capture technology used.

5.2.1 Tank for low pressure gaseous CO_2

For the low-pressure case, the tank for gaseous CO_2 will be the first knock-out drum in the compressor train which is the first part of the liquefaction plant as shown in Figure 31. The sizing of the knockout drums will depend on the flow and the level of entrained liquid. The operating pressure of the tank will be kept marginally lower than the pipeline pressure to ensure flow.

For return gas from a ship being loaded, the head space of the cargo tanks will serve as tanks for gaseous CO_2.

5.2.2 Tank for high pressure gaseous CO_2

For the high-pressure case, the system will be a two-phase separator where the pressure is reduced to the ship transport pressure. The gas stream from the separator is recompressed and condensed and recycled back to the inlet of the separator, as shown in Figure 30.

The cooling water requirement is calculated based on incoming cooling water temperature of 20°C and outgoing temperature of 30°C. Power and cooling water requirement per tonne CO_2 is shown for two different outlet pressures in Table 34.

Table 34 Power and cooling water requirement for different outlet pressure to storage tank

CO_2 inlet P	CO_2 inlet T	CO_2 outlet P	CO_2 outlet T	Power consumption	CW consumption
80 barg	5°C	15 barg	-26°C	17.6 kWh/t	3.15 m^3/h·t
80 barg	5°C	6.5 barg	-47°C	57.4 kWh/t	7.62 m^3/h·t

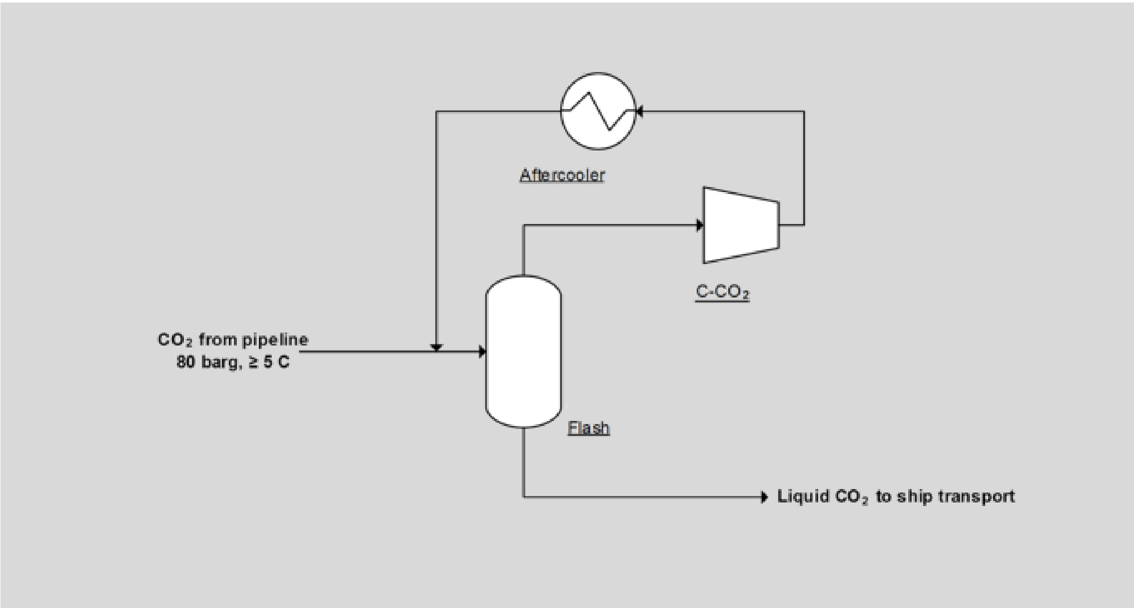


Figure 30 Process for the conditioning of high-pressure CO_2 for ship transport

5.3 Liquefaction

A liquefaction system will be needed. The needed capacity will depend on the complexity of the terminal. If the terminal is a storage facility for liquid CO_2, the dimensioning case for the liquefaction plant is the BOG from the storage tanks and the displaced gas from the filling of the storage tanks from shore.

If the terminals receive gas from a pipeline the liquefaction plant needs to match the capacity of the pipeline.

From the design basis, chapter 2.2.6, the following dimensioning factors are mentioned:

- Boil off gas rate
- Fraction arriving to the terminal in gas phase
- Incoming pressure
- Fraction arriving in liquid phase
- Displaced gas volumes during loading of the terminal
- Design pressure and temperature of the storage tanks
- Choice of refrigerant with respect to GWP
- Gas return from the ship being loaded
- Pressure on incoming gas stream

The liquefaction process will be based on the liquefaction process described in WP1- Cost estimation tool for CCS scenarios, ref (38) as shown in Figure 31. This work package includes tools for estimating size and cost of conditioning for ship transport among other utilities.

The refrigerant used in this case is ammonia (NH_3), or R717 as is the alternative name. The normal boiling point of ammonia is – 33°C. NH_3 as a refrigerant has the advantage over the traditional fluorocarbons that the global warming potential (GWP) is 0. NH_3 is toxic and gas detectors shall be fitted. The alarm limit shall be 150ppm, ref. (39) and (40). The materials used for refrigerant piping shall be compatible with ammonia.

The ammonia refrigeration circuit consists of:

- Compressor
- Condenser
- Separator with buffer capacity for refrigerant (not shown in Figure 31)
- Throttle valve
- Evaporator (CO_2/NH_3 cooler in Figure 31)

This means that depending on the target CO_2 pressure, the refrigeration circuit will be a partly open circuit, this is illustrated in Figure 31. The CO_2 needs to be compressed to at least 16 barg to achieve condensation using evaporating ammonia at 0 barg as the cold stream in the condenser. The liquid CO_2 is then flashed to the required storage pressure and the Joule – Thomson effect will cool the CO_2 and a fraction of the stream will evaporate and be recycled to the suction side of the compressor matching the pressure. The number of compression steps will depend on the inlet pressure of the gas. The pressure received from a capture plant is often less than 1 barg, in which case the numbers of compressors in the compressor train will be as shown in Figure 31. This will be the case if the terminal is close to a capture plant. Here, the capacity will need to match the capture plant.

Another case could be that the terminal is placed close to a pipeline, transporting gaseous CO_2. In this case the capacity of the liquefaction plant will need to match the pipeline capacity. The number of compression steps depends on the pipeline pressure.

If the pipeline pressure is above the critical pressure, which is usually the case for transport over longer distances, the pressure must be reduced to the required storage pressure. As a result of this pressure reduction a fraction of the incoming flow is liquefied, and the rest shall be recompressed and cooled and mixed with the incoming flow. This is further explained in chapter 5.2 and described in Figure 30.

If re-liquefaction is the dimensioning case, there will be less compressors as the inlet pressure is higher and the capacity will be smaller. In this case a buffer gas tank may be needed.

After each compression step there is an intercooler and a knock-out drum. The purpose of this is two-fold, to reduce the suction temperature between the compression steps and to reduce the water content in the CO_2.

Depending on the potential impurities in the incoming streams other purification steps may be necessary, examples are:

- Molecular sieve driers to reduce the water content even further
- Removal of H_2S by active carbon filters
- Removal of CO by flashing

The investment cost and the operating cost will depend on which of the scenarios will be relevant for the design of the refrigeration plant.

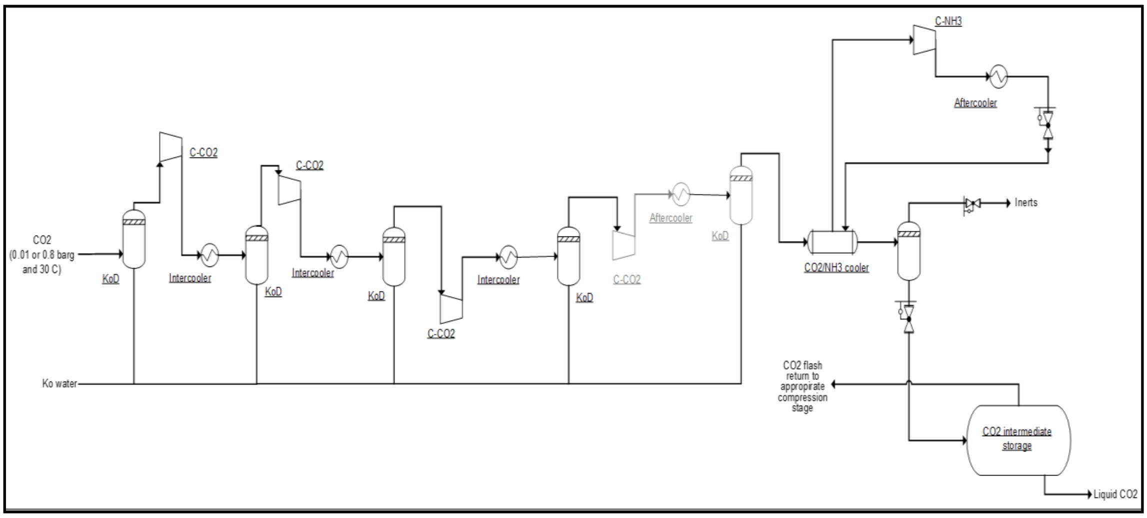


Figure 31 Simplified flow sheet of the liquefaction system as used in work package 1

5.4 FSRU integration

If the terminal is located in the vicinity of a floating storage and gasification unit (FSRU) for natural gas, energy savings can be achieved by using the CO_2 as heating medium for the gasification and thereby liquify the gas. Here the CO_2 must be compressed to the transport pressure before entering the heat exchanger.

This integration is dependent on the availability of CO_2 in gas phase and of LNG.

For the calculation purpose LNG is simulated as methane. The reason for this is that the LNG specification is wide and that the content of heavier components varies based on area.

Due to the very low temperature of the LNG, care must be taken to avoid formation of dry ice.

For more details see chapter 4.

5.5 Instrument air & service air

This system consists mainly of air compressors. Normally 2x100 % compressor capacity is installed.

The normal air pressure in the distribution net is approximately 7.5 barg. This requires an outlet pressure from the air compressors overcome the pressure drop across dryers, accumulators and control valves.

For the instrument air a set of air driers are required. The required dew point of the air is dependent on the location and the minimum ambient air temperature. The air consumption may be estimated once the process requirements have been established.

If a nitrogen generator is installed on board, the capacity of the air compressors needs to cover the required inlet air for this.

5.6 Sea water cooling system

If no cooling water is available from shore, a sea water cooling system must be installed. The sea water cooling system is supplied from sea chests and provides cooling water for some direct consumers and for the closed loop freshwater cooling system on board. As a minimum this will consist of a sea chest, sea water pumps and two parallel coolers for the freshwater cooling circuit. A system for marine growth prevention shall be included.

When the location of the terminal is known, it is important to take the sea water quality into account when designing the coolers to account for potential fouling.

5.7 Freshwater cooling system

If no cooling water is available from shore, a freshwater cooling system shall be installed on board. This is a closed loop system where freshwater with added corrosion inhibitor is circulated to the consumers and excessive heat is removed by the seawater coolers.

5.8 Potable water generation system

If the terminal is located in a remote area, fresh water might not be available. If this is the case, a system for generating potable water from seawater with a minimum capacity of 200 litre/person/day shall be installed.

Topping up of the closed loop freshwater cooling system and providing potable water to visiting ships may also be required.

A reverse osmosis unit is normally used for such production. This unit runs sea water through membranes producing water with a conductivity of less than 75 mS/m at 25°C.

A simplified sketch of such a system is shown in Figure 32.

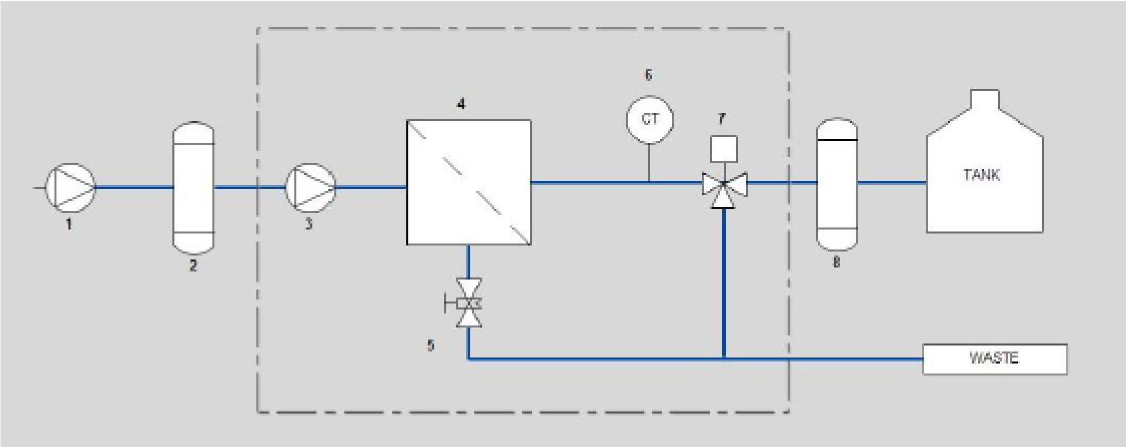


Figure 32 Simplified sketch of a typical RO unit from Norwater

- Seawater feed booster pump.
- Prefiltration.
- High pressure seawater pump.
- Membranes.
- Pressure control valve.
- Conductivity sensor.
- Diverter valve for out of specification water.
- Post treatment pH adjustment.

5.9 Bunkering system

If the terminal is at a remote location, being able to provide bunkers could be a requirement. Fuel for power generation on the terminal may also be needed.

If ammonia or methanol is the fuel to be offered, nitrogen will be needed for the bunkering system, for flushing of bunkering lines after bunkering.

For potential power generation for the terminal, diesel is chosen at this stage as this is commercially available. However, alternative fuels such as methanol and ammonia will soon be available for power generation.

The fuel bunkering tank needs to be equipped with deepwell pumps and these will need 2x 100% sparing.

In addition, for the liquified gases, a gas return system and a dedicated liquefaction system is required.

Storage capacity shall be for 3 months. Type of fuel will vary from case to case.

The storage tank size will depend on consumption, on re-fill frequency, but also on energy density. Energy density of different fuels is shown in Figure 33.

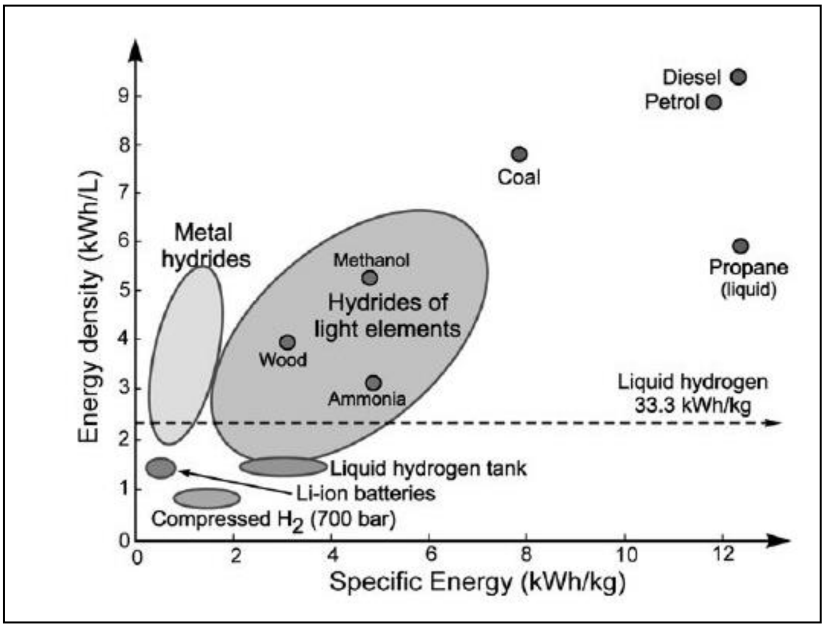


Figure 33 Energy density for different fuels, ref. (41)

The size of the storage tank will depend on the fuel chosen as bunkers.

The complexity of the fuel system will depend on the fuel chosen.

It is important to remember that ammonia is toxic and that the following requirements comes into force:

> The vent mast from the tank safety valves shall be *"The outlet from the vent mast shall be located at least B (greatest moulded breadth) or 25 m, whichever is less, from the nearest air intake, air outlet or opening to enclosed spaces on the vessel."*, ref. (40).
> The fuel supply system shall include an ammonia release mitigation system (ARMS). This system shall handle purging and drainage from fuel piping, bleeding from double block and bleed arrangements, releases from PSV's on piping and other operational releases of ammonia. Maximum released concentration for the ARMS system shall be no higher than 30 ppm.

In addition, a BOG liquefaction plant is needed.

For other cryogenic fuels, protection of the hull from the cold, may be an issue.

5.10 Fire water system

A firewater system will be required. This system will have a separate pump driven by a diesel engine and this pump takes suction from the sea chest.

The fuel system if installed will need sprinkler systems and the bunkering system will need a water curtain. The LQ will also need fire protection.

5.11 Waste handling

This will consist of a collection tank and pump. The size will vary from case to case.

5.12 Power supply, from shore or generator

The choice of power supply depends on the availability, cost, and carbon intensity of the power at the site. The power demand will be based on the sum of power demand for the separate modules and the number of modules selected for each case.

The black bars in Figure 34, show the average carbon intensity of electricity generation in 2020 for each of the EU countries. The map in Figure 35, shows the carbon intensity worldwide.

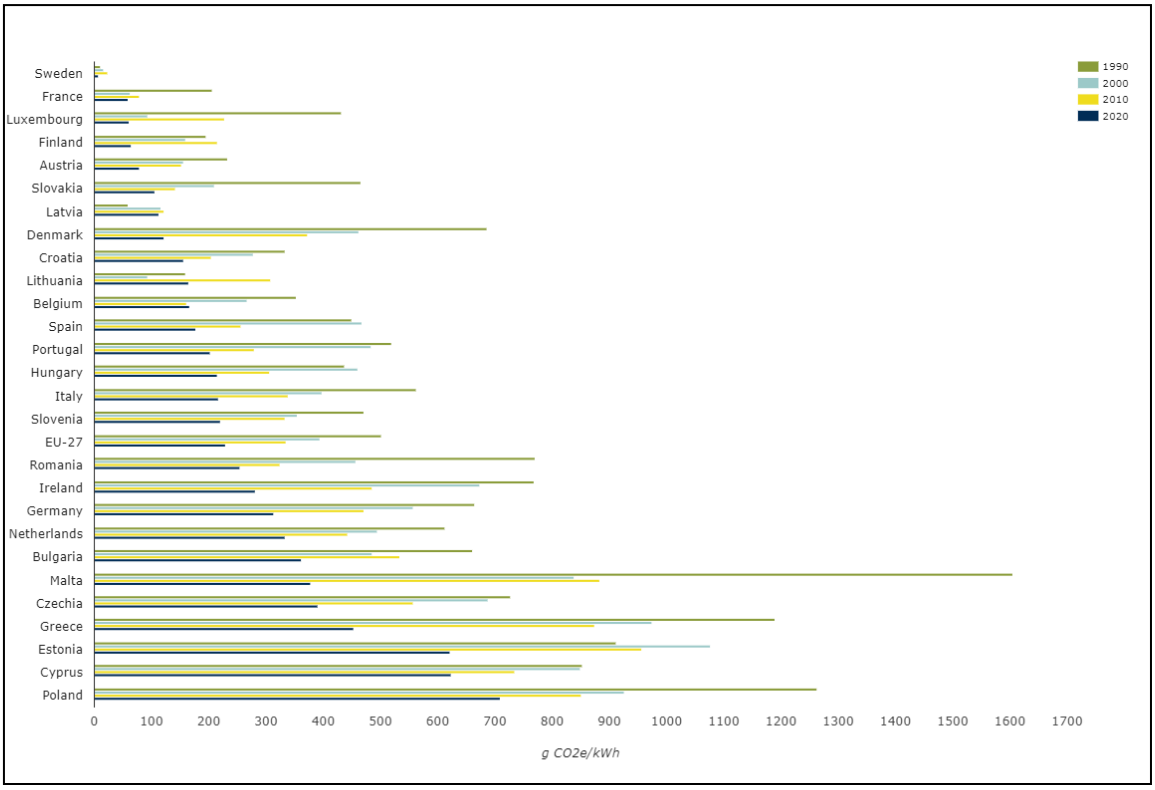


Figure 34 Greenhouse gas intensity of electricity generation in the EU, ref. (42)

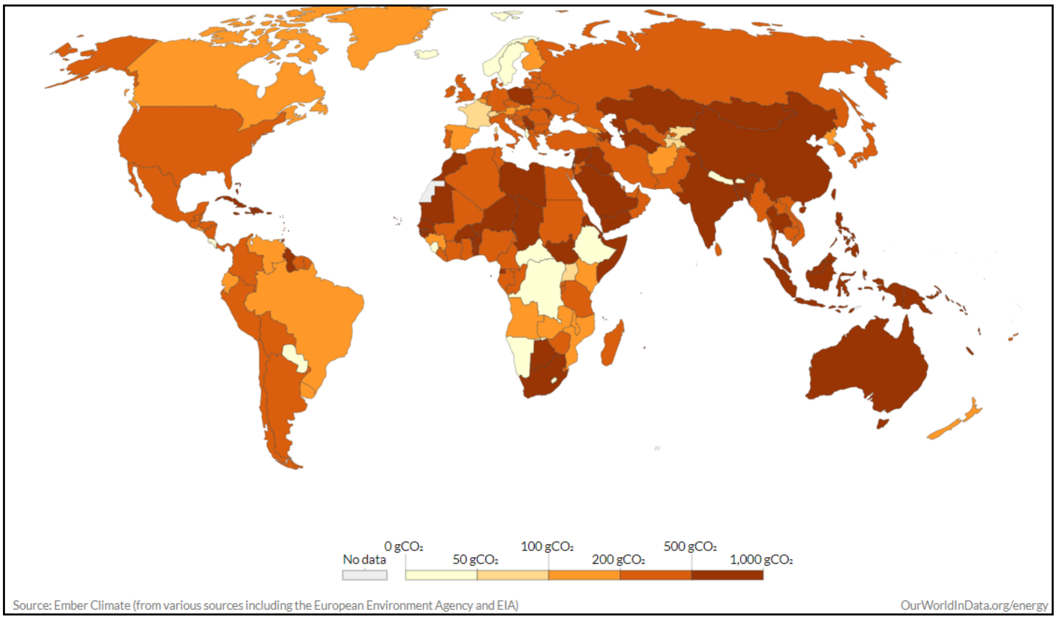


Figure 35 Carbon intensity of electricity 2021, ref. (43)

The carbon intensity of electrical generation using a generator based on diesel is in the area 610-720 gCO_2/kWh. This is based on data from FW Power, ref. (44) and MAN 6L23/30H, mk.2, ref. (45).

To find numbers for the other possible fuels, the numbers are adjusted based on the heating value found in, ref. (46) and (47).

Table 35 CO_2 release from generator at different loads

	Heating value, MJ/kg	Average Heating value	g CO_2/kg fuel consumed	Low con-sumption, g/kWh	High con-sumption g/kWh	gCO_2/kWh low	gCO_2/kWh high
Diesel	42-46	44	3.17	192	226	609	717
LNG	42-55	48.5	2.75	174	205	479	564
Methanol	22.7	22.7	1.375	372	438	512	602
Ammonia	18.6	18.6	0	454	534	0	0

Based on Table 35, shore power shall be preferred (in most countries), unless green or blue ammonia or biofuel replacements for the hydrocarbon derivatives from sustainable sources are available.

Therefore, the decision on whether to have a dedicated module for production of electrical power or use electricity from shore depends on the availability of electrical power from shore.

If electricity must be generated on board, the alternatives are to run the generator by a diesel engine or a gas turbine. It must be kept in mind that a fuel tank for the generator will be needed. For this estimate, a diesel driven generator is assumed with a fuel tank capacity sufficient for 3 months of power production. Bio diesel from sustainable sources and potential carbon capture shall be evaluated.

Here CO_2 capture could be evaluated. To be able to do this work, it is important to know the running profile of the powerplant as the turn down capability of a conventional capture plant may be limited due to the absorption and stripper columns. This work is considered to be outside the scope of this work package.

6 SHORE AND SHIP CONNECTIONS DESIGN

6.1 Interface elements

The floating terminal is designed for operating in protected waters (inshore)or in a remote area 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 relative to the surroundings.

6.1.1 Mooring

There are several ways a ship can be fixed to the terminal both using ropes and lines but also using vacuum and electromagnetic systems. All the mooring systems come with advantages and challenges, and it is important to evaluate the given assumptions for a case before choosing the mooring type. Conventional mooring arrangements consist of ropes and wires of required strength that enables the vessels to moor safely along the terminal. The non-line methods save time, berthing space, tug handling operations and may improve safety.

6.1.2 CO_2 handling

Conventional loading by flexible hoses or loading arms of pressurized liquified gas at low temperatures is a well-known technology. As the volumes for loading and unloading liquefied CO_2 per now is limited, the CO_2 is handled with flexible hoses. For the Northern Light project that is under construction, loading arms are suggested. The CO_2 handling involves both liquid and gaseous CO_2.

6.1.3 Electrical power

Supply of electrical power to the ship for general consumers (hotel functions) onboard when connected to the terminal/ in port is commonly used to reduce the need for running onboard fossil fuel generators. This to reduce local emissions and reduce the GHG footprint. The capacity of the shore power link is usually limited to the load required by the hotel functions. Recently vessels have started to include batteries in their power systems to further reduce GHG emissions. The terminal facilities may also be required to support charging these batteries. There are also solutions where the batteries are charged by the ships main engines during transit to be able to run on battery power when leaving/approaching port. The shore power link and the system for charging of batteries will normally be separate systems. The system can be conventional shore power connection system or automated shore power connection.

6.1.4 Potable water

Conventionally the connections for potable water and sewage to shore facility are made manually with flexible hoses. This requires manpower in port. Automated solutions for these are not commonly used.

6.1.5 Bunkering of fuel

Provided the ship is equipped with a combustion engine, bunkering of the relevant fuel is required. Bunkering is normally done, either from the shore terminal or from a bunkering vessel, through loading arms or flexible hoses handled manually and/or with cranes and derricks.

6.1.6 Provisions

Provisions are manually brought onboard either by cranes or forklifts. In the future It might be beneficial to look at if this process can be further automated and if the environmental impact related to waste from containment and wrapping of the provisions may be reduced.

7 APPENDIX 1: GENERAL ARRANGEMENT OF CASES A AND B

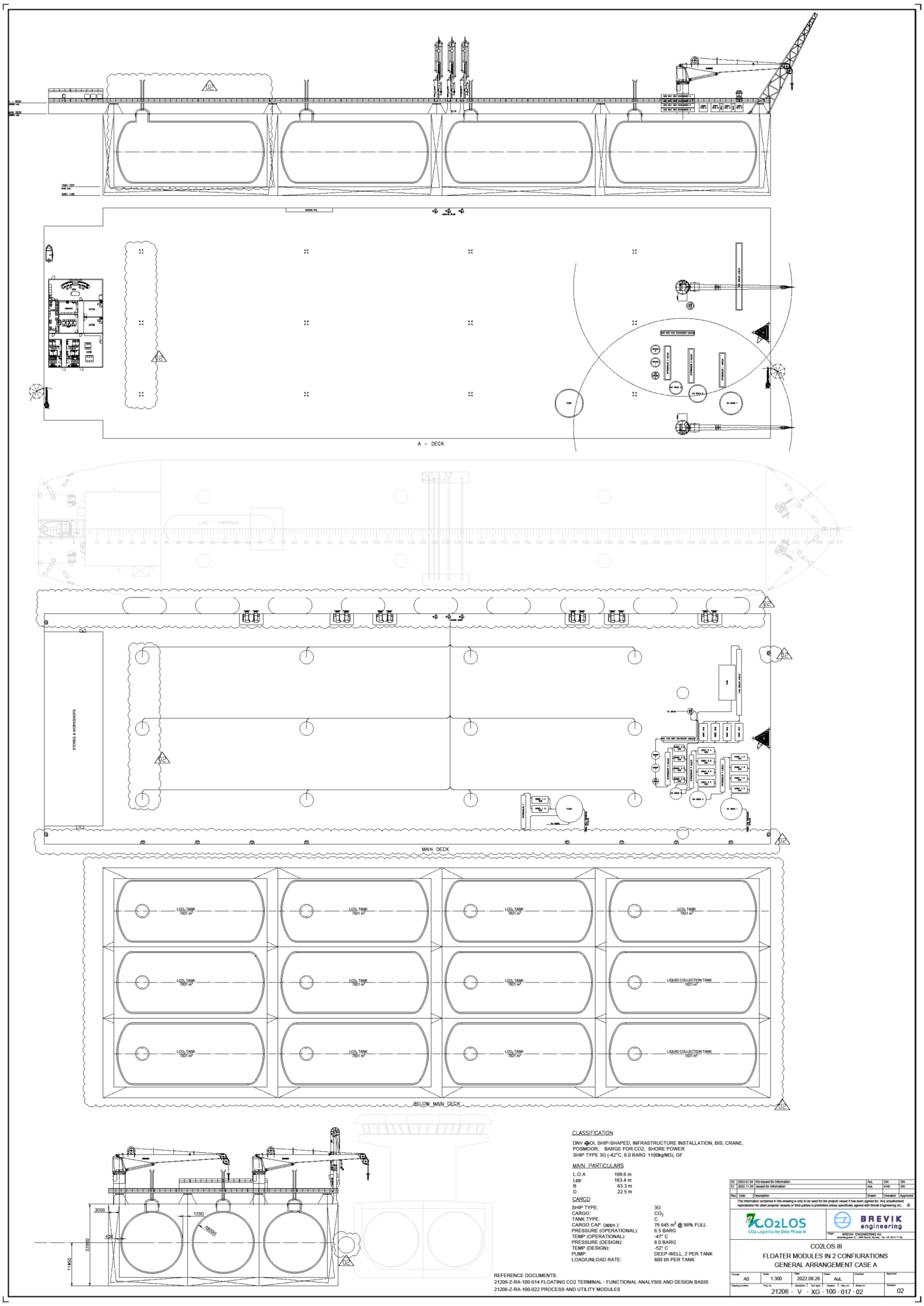


Figure 36 General Arrangement Case A

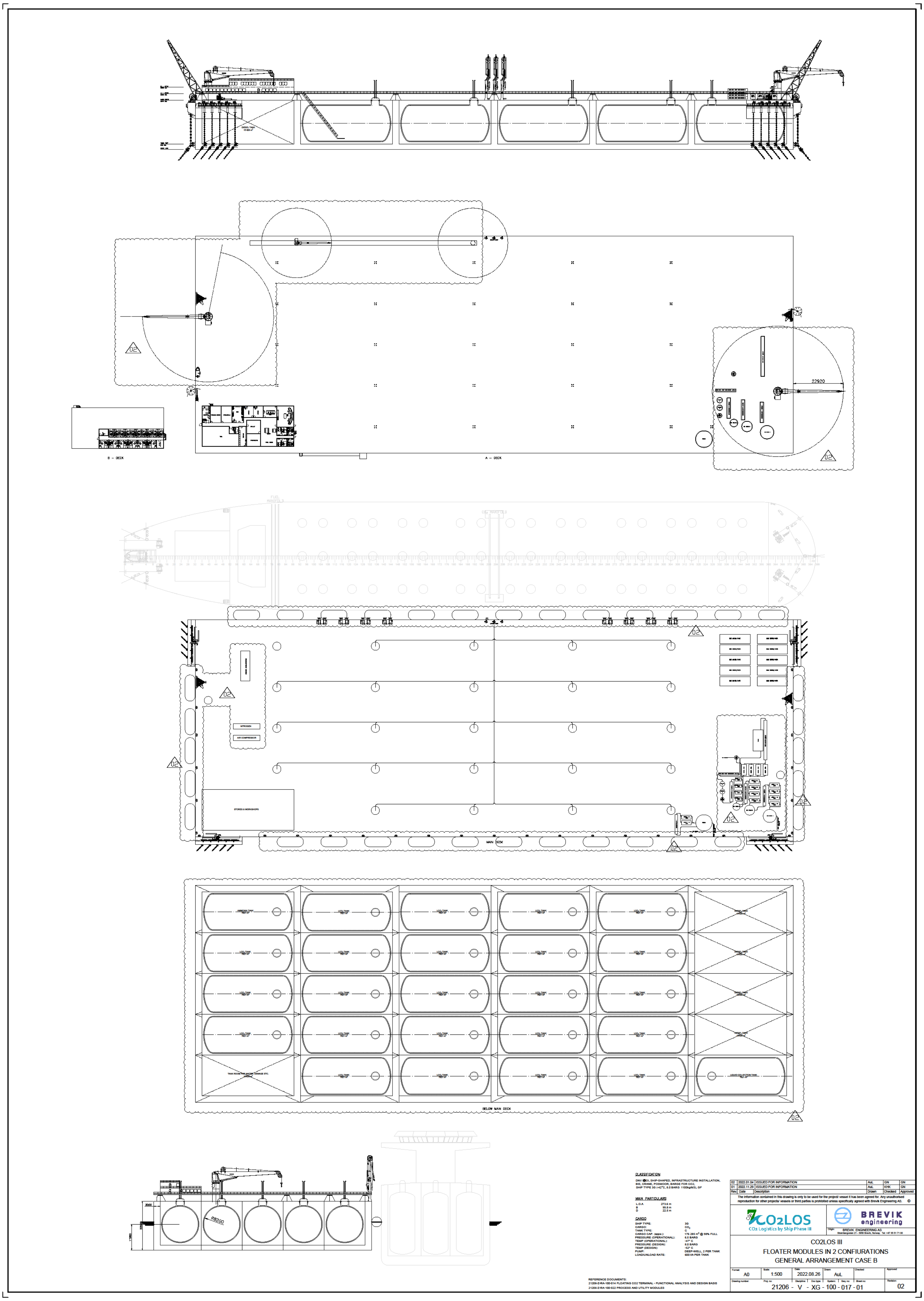


Figure 37 General Arrangement Case B

WP4 – ZERO EMISSION SHIPPING

1 INTRODUCTION

In this work package technologies that, if implemented, can contribute to low or zero emission from the shipping industry are discussed. The main categories of such technologies are ship optimisation, fuel-shift, and onboard CO_2 capture. If zero emission shipping is to be achieved, it is likely that more than one of these technologies needs to be implemented. While low emission shipping could be reached through the introduction of only one. Still, the cost level, implementation challenges, and HSE aspect have not been discussed here and needs assessed further to identify the actual potential of the different technologies.

2 LOW EMISSION VERSUS ZERO EMISSION SHIPPING

The initial name of the WP that this delivery represents is "Zero emission shipping", however in reality zero emission can only be achieved through fuel-switch to a fuel with zero carbon footprint, or through acquisition of CO_2 removal credits from companies that provide such services. One such example is Climeworks, ref. (48), a company that captures CO_2 from air and permanently store it underground, and then sells CO_2 removal credits to companies that either have no direct emissions (scope 1 and 2) to abate or have hard-to-abate emissions. Hard-to-abate is defined as emissions that are disproportionately costly to abate or impossible to reduce with currently available technologies. All sectors do, to some degree have hard-to-abate emissions, especially if the reference is zero emissions.

To get a better understanding of how difficult it might be to reach zero emission shipping one must first understand how GHG emissions could be accounted for. The accounting standards developed by Greenhouse Gas Protocol (a joint initiative of World Resources Institute, WRI, and WBCSD) are fast becoming the most widely used standard for the private and public sector (49). The standard divides the greenhouse gas emissions into Scope 1, 2, and 3 based on their origin. Scope 1 are direct emissions from the core business (owned or controlled sources), Scope 2 are indirect emissions from the generation of purchased energy consumed, and Scope 3 are all other indirect emissions that occur in the value chain (3). Scope 1, 2 and 3 emissions are illustrated in Figure 5-1.

The figure illustrates the potential difficulty of achieving zero emission shipping, even if one is able to completely abate Scope 1 and 2 emissions, complete abatement of Scope 3 is challenging.

In this report, technologies that target abatement of Scope 1 emissions are the primary target. However, for some of them this could result in a shift from Scope 1 to 2, i.e., from direct to indirect emissions. An example of this is battery driven ships where the electricity used will have a CO_2 emission factor.

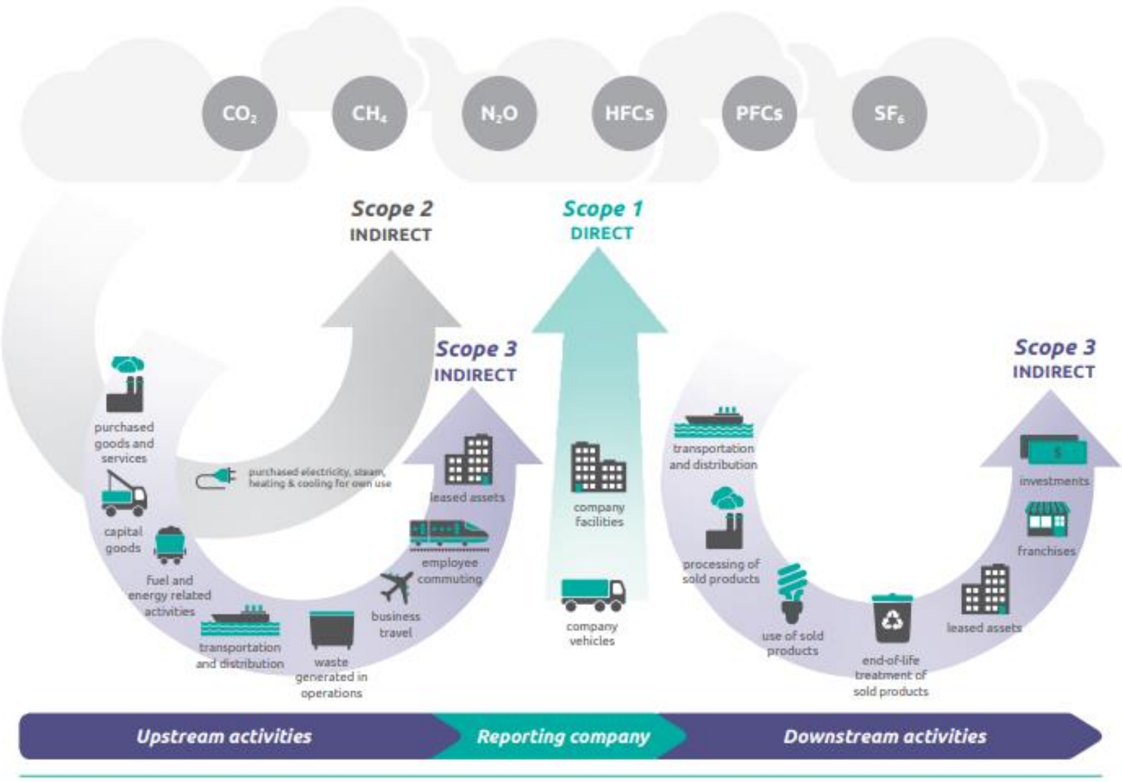


Figure 38 Illustration of Scope 1, 2, 3 emissions according to Greenhouse Gas Protocol (3)

3 CURRENT AND FUTURE FRAMEWORK

Maritime transport is a key element in global trade and benefits from being one of the most energy efficient modes of transport. Still, the shipping industry accounts for about 3 % of the annual anthropogenic GHG emissions and emitted 1 076 Mt CO_2 in 2018, ref. (2). There are currently no global laws and regulations in place that promote the implementation of low or zero emission technologies in the shipping industry. The International Maritime Organization (IMO) proposed a strategy in 2018 where the ultimate goal is to phase out GHG emissions from shipping. A more disruptive measure potentially being realised already from 2024, is the implementation of shipping emissions into the EU ETS (Emission Trading System).

3.1 IMO goals

In 2018, the IMO adopted an initial strategy to reduce, and eventually phase out GHG emissions from ships. The strategy has three goals:

- A reduction in carbon intensity of international shipping by at least 40 % by 2030 compared to 2008
- Pursuing efforts to achieve a 70 per cent reduction by 2050, compared to 2008
- Reduce the total annual GHG emissions from international shipping by at least 50 percent by 2050

To achieve these targets, the following amendments have been included in the Pollution Prevention Treaty (MARPOL):

Energy Efficiency Design Index (EEDI): New ships must be built and designed to be more energy efficient

Ship Energy Efficiency Management Plan (SEEMP): A practical tool for helping shipowners manage their environmental performance and improve operational efficiency

Energy Efficiency Existing Ship Index (EEXI): Set to enter into force in 2023, EEXI applies many of the same design requirements as the EEDI, with some adaptations regarding limited access to design data

The Fuel Oil Consumption Data Collection System (DCS): Mandates annual reporting of CO_2 emissions and other activity data and ship particulars for all ships above 5 000 GT

Carbon Intensity Indicator (CII) is a rating scheme (A-E) developed by the IMO to measure the annual performance of all ships above 5 000 GT in terms of CO_2 per DWT and distance covered

The SEEMP, DCS, and CII are operational measures. The EEXI is a measure to bring existing ships into line with the goals, and the EEDI is a measure to ensure that new built ships comply with the goals.

3.2 EU

Emissions from ships operating within maritime transport in the EU and the European Economic Area (EEA) is likely to be implemented into the EU Emission Trading System (EU ETS), ref. (2). A provisional agreement to strengthen the EU ETS and implement new sectors into the trading system was reached by co-legislators on December 17th, 2022. If this agreement is formally adopted, maritime transport will become a part of EU ETS in 2024.

An overview to the implementation of EU ETS into the shipping sector is provided by DNV, ref. (50). Here a map is provided illustrating how much of emissions that would need to be reported depending on whether the ships operate within or transport cargo/people to the EU/EEA, see Figure 39.

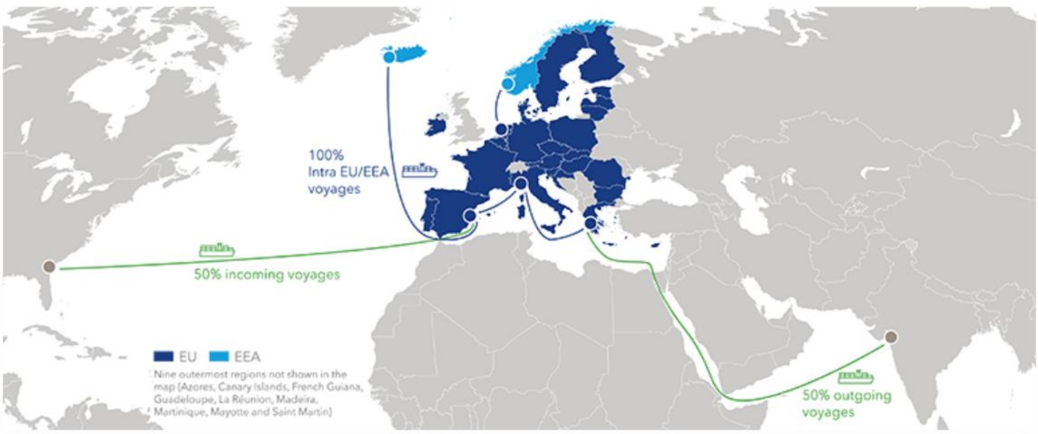


Figure 39 An overview provided by DNV illustrating the implications of EU ETS (50)

Further, DNV also provide an overview of the planned implementation timeline, see Figure 40.

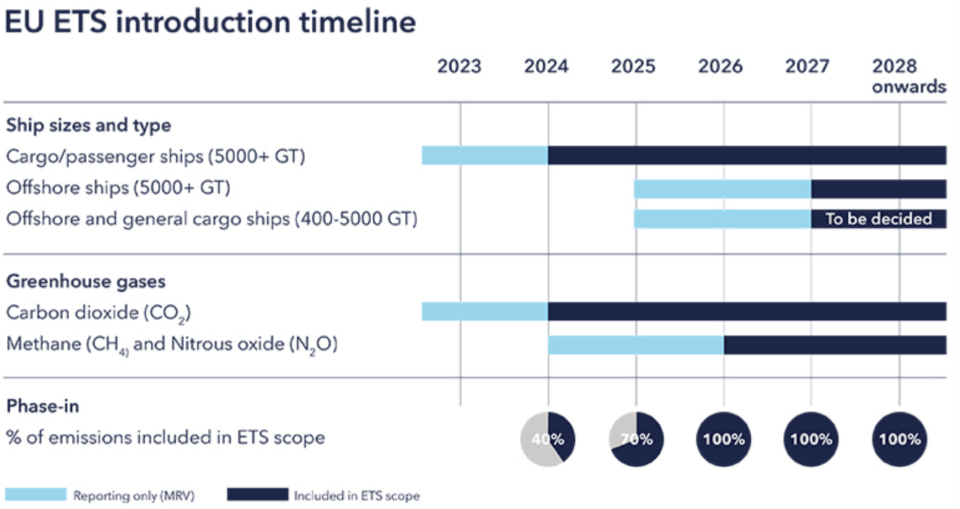


Figure 40 The planned EU ETS implementation timeline as provided by DNV (50)

In Figure 6-2 the implementation according to type of ship, ship size, type of GHG, and % of emissions included in the ETS scope. From 2024, it is expected that cargo and passenger ships larger than 5 000 GT will need to report CO_2 emissions where 40 % will be included in the ETS scope.

In addition, a provisional political agreement between the EU Council and the European Parliament was reached in March 2023 on the FuelEU Maritime Initiative. The FuelEU Martime initiative is a part of the "Fit for 55" package where the EU aims at a net reduction in greenhouse gas emissions of 55 % by 2030 compared to 1990 and climate neutrality by 2050, ref. (51). The implementation of the FuelEU Maritime initiative should facilitate for a fuel-switch in the maritime sector to more renewable and low-carbon fuels, without disrupting the internal (EU) market.

4 EMISSIONS IN THE CO_2 SHIPPING INDUSTRY

In the first section of this chapter, the battery limit of what emissions are considered for CO_2 shipping is presented. Following this, the identified emissions are described and discussed.

4.1 Battery limit

The battery limit is shown in Figure 7-1. Here, only emissions that are related to the part of the shipping operation where the cargo ship is in transit are included. This means that emissions that occur during loading and unloading of CO_2 is disregarded. Further, it is also assumed that the ship is supplied with electricity from land while it is moored at either side of the transport chain.

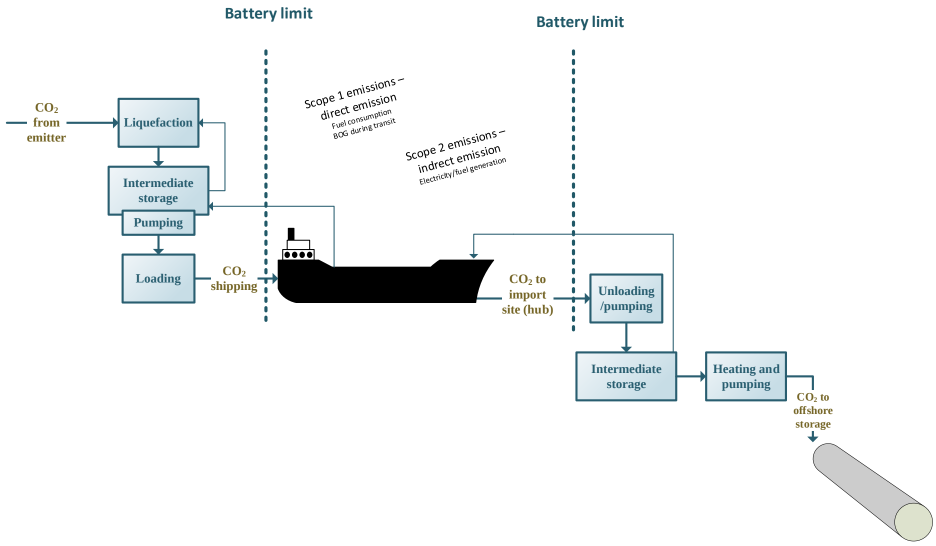


Figure 41 The battery limit of the CO_2 emissions considered in this study

With reference to the GHG emission standard by GHG Protocol discussed in Chapter 5, fuel consumption during transit and boil-off-gas is defined to be Scope 1 emissions (direct emissions) and emissions due to generation of electricity and fuel are defined to be Scope 2 emissions.

4.2 Emissions from CO_2 cargo shipping

CO_2 cargo shipping is a well-known operation in the food and beverage industry, with ships having been in operation for more than 30 years, albeit on a relatively small scale. In the future however, CO_2 transport by ship is expected to become a lot more common due to the last decade's increased focus on CCS (carbon capture and storage) as one of the technologies needed to abate the CO_2 emitted to the atmosphere. The implementation of a CCS chain will likely include transportation of CO_2 from an emitter to a site for permanent storage and for this purpose, CO_2 cargo ships are expected to play a vital role.

4.2.1 Fuel consumption

In this section typical fuel types and their associated CO_2 emissions are discussed on a general basis. Currently, most ships are fueled by fossil fuels. Marine diesel oil (MDO) consists of ~86 % carbon, which when combusted, gives about 3.2 tons of CO_2 per ton of fuel. Since the carbon content of heavy fuel oil (HFO) is slightly higher, the CO_2 emissions are even higher for HFO. An example of the amount of CO_2 emitted for a HDO ship with an engine size of 5 000 kW that operates at 80 % of its max power is showed. As a rule of thumb, the specific fuel consumption in diesel driven combustion engines may be approx. 0.2 kg/ kWh. Then the ship will emit 0.2 kg/kWh x 80 % x 5 000 kW x 3.2 = 2 400 kg CO_2 per hour. If the ship is running on LNG, the emission will be lower, as the emission factor for LNG is 2.75 ton CO_2 per ton of LNG. In addition to this, there will be emissions also from the generation of the fuels.

4.2.1.1 The Northern Lights ships

The two ships being built by Northern Lights for use in the Longship project, are according to, ref. (52), going to be LNG-fueled. In addition, they will be equipped with wind-assisted propulsion systems and air lubrication technology. It is expected that this will reduce the CO_2 emissions with 34% compared to more conventional systems, ref. (52). The ships will be designed to operate as close as possible to EEDI phase 3, ref. (53).

4.2.2 Boil-off-gas

4.2.2.1 CO_2 storage tanks

The discussion here is limited to boil-off-gas issues relevant for a CO_2 cargo ship, i.e., related to BOG from fuel storage tanks and the CO_2 cargo tanks during shipping operation.

During storage and transportation of cold liquid CO_2 the storage tanks will be exposed to surrounding atmosphere temperature and will continuously vaporize. Consequently, the pressure inside the tank will increase over time and at a certain pressure level, pressure safety valves (PSVs) will enable the release of vaporized CO_2, as BOG from the tank to avoid overpressure in the tank. The rate of vaporization depends on the rate of heat ingress from the surroundings.

A CO_2 storage tank inside the cargo hull will be surrounded by a layer of stagnant air increasing the effective insulation. Heat transfer models developed for such a case show the vaporization is slow and that that the ship can operated for several weeks without pressure release due to BOG. Calculations show that liquified CO_2 at-50 °C and 6 barg pressure can be stored for 46 days before pressure have reached 7 barg (-46 °C) and pressure release would be necessary, ref. (54). See also Table 36.

Table 36 Resulting pressure build up in CO_2 storage tank due to heating. (According to ref. (54))

Loading pressure	Set point for pressure release valves	Possibility for pressure accumulation	Heat flow into a single tank	Number of days	Number of cargo tanksn_T	Mass flow BOG per cargo tank
6 barg	7 barg	Yes	11.8 kW	46	2	0*

4.2.2.2 Fuel storage tanks

In addition to possible emissions from the CO_2 cargo tanks, it is also worth to mention that BOG from any fuel storage tanks onboard also needs to be monitored and limited. In the case of an LNG fuelled ship the BOG will be methane. The LNG fuel for the ship propulsion can be stored in pressurized tanks (C-type tanks) on deck. IMO regulations require minimum of 15 days storage without venting BOG when the fuel system is in stand-by mode. Different systems for LNG boil-off gas utilization have been proposed to avoid emissions. It can be re-routed to use in one engine, used for heating or re-liquified and returned to the tank, ref. (55).

5 LOW AND ZERO EMISSION TECHNOLOGIES

In this chapter technologies that can enable low and zero CO_2 emission from ship operation are presented and discussed. However, adopting new technologies for the purpose of reducing CO_2 emissions might result in increased emission of other GHGs (methane, nitrous oxide, hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs) and ozone) and thereby reducing the overall impact. Further, implementing some technologies might also generate significant amounts of waste and/or hazardous waste.

5.1 Ship optimization

Emission reduction, while still utilizing traditional fuel types, requires viewing the ship as a system, and using techniques and technologies that complement each other, to maximize the overall efficiency of the vessel. Below several techniques and technologies which may be combined for optimization are presented. Which elements are used will depend on the type, and operational profile of the vessel in question.

5.1.1 Engine efficiency improvement

The most efficient marine engines today achieve an overall energy conversion efficiency of 54.4 %. This may be increased slightly, with further development, but is nearing the theoretical limit for an internal combustion engine. The most realistic and cost-effective way to increase engine, or fuel efficiency, is to utilize waste heat recovery. This is a technique where the heat from the engine exhaust is utilized for energy.

5.1.2 Operational profile

An easy way to reduce emissions from ships is to adjust the way the ships are operated.

There are several ways of doing this:

Slow Steaming - the practice of operating transoceanic cargo ships, especially container ships, at significantly less than their maximum speed. Lowering speed reduces fuel consumption because the drag of the ship increases at a much greater rate than the speed.

However, although lowering speeds reduces the power requirements, the overall benefits of speed reduction may be limited by other factors, such as economically viable total voyage time, and the fact that a ship's engine and propeller are designed to operate within a certain RPM range. Steaming too slowly may place the engine and propeller outside their most efficient range and will therefore begin to counteract the benefits.

Smart Steaming – a variant of slow steaming, it is a strategy by which the vessel speed is dynamically optimized based on the real-time state of the sea, weather, and the destination port - for example, if there is congestion at the port there is little point in rushing to get there at full speed simply to then wait for a berth for days. Instead, the ship can go more slowly to conserve fuel and still berth at the same time. Some examples of smart steaming show up to 30 % reduction in fuel usage for the ship.

Weather Routing - Ship weather routing is used to develop an optimum track for ocean voyages based on forecasts of weather, sea conditions, and a ship's individual characteristics for a particular transit. It can be used to optimize the route for reduced fuel consumption, by utilizing the wind and currents.

For vessels using wind assistance, weather routing will greatly increase the possible fuel savings, and emission reductions.

5.1.3 Wind assistance

Wind assistance covers several different vessel ambitions:

Wind-Assisted Motor Vessels – primarily employing auxiliary-wind propulsion systems retrofitted onto existing vessels. These systems offer fuel savings in the 10-30 % range, with lower initial retrofit investment costs than new build options.

Hybrid Wind/Motor Vessels – these designs combine fuel and emissions reduction benefits of wind propulsion options with the capabilities and performance of motor vessels allowing predictable scheduling. In favourable winds savings can be in excess of 60-70 %, in less accommodating conditions vessels use a mix of wind/motor propulsion or motor alone. With good weather-routing and handling, new build sailing hybrid vessels are defined as offering fuel savings on an annual basis of over 50 %.

Purely Wind Vessel (+Auxiliary Motor) – these vessels can deliver up to 100 % savings, with lower maintenance costs etc. however the challenge of maintaining schedules and being susceptible to weather conditions are important considerations.

At the present time there are 23 ships trading commercially with some type of wind assistance installed. During the next year, another 23 ships will be launched, or retrofitted with wind assistance. Most of these vessels are wind assisted motor vessels, using the assistance to reduce, but not eliminate the fuel consumption. However, there are more ambitious projects under development, and building, including projects that expect to achieve up to 90 % emission reductions, ref. (56).

The types of equipment include Flettner rotors, suction wings, fixed wing sails with 1, 2, or 3 sections, soft wing sails, and kites.

Flettner Rotor - a smooth cylinder with disc end plates which is rotated by a small engine, around its axis, and, as air passes at right angles across it, the Magnus effect causes an aerodynamic lift to be generated in the direction perpendicular to both the axis and the direction of airflow, ref. (57). The lift can be controlled by varying the rotational speed, and may be adjusted to give 0 lift, thereby in effect "reefing" the sail. The sail may be mounted to tilt, in order to pass under bridges, or to reduce windage.

Suction Wings – these are based on the principle of boundary layer suction. The wings are non-rotating suction wings with vents and an internal fan (or other device) that uses boundary layer suction for maximum effect to generate thrust for the ship. (58). The concept utilizes high lift wing sections, and the use of boundary layer suction delays the flow separation from the wing, which reduces drag. The lift may be adjusted by varying the suction, and by feathering the sail. The sail may be mounted to tilt, in order to pass under bridges, or to reduce windage.

Fixed Wing Sails – wing section mast/sail. These may be made of 1, 2 or 3 sections. The multi-section profiles have variable camber, similar to aircraft wings, which are adjusted to vary the lift and drag. They may be reefed by telescoping or feathering. The sail may be mounted to tilt, in order to pass under bridges, or to reduce windage.

Soft Wing Sails – wing sails made of 1 section, that produces lift by having an angle of attack to the wind, but is collapsible, so the air draught of the vessel is not affected.

Kites – these are inflated parafoil kites, deployed from the bow of the ship, and flown in a figure eight, in the same manner as a kite-surfing kite. The lift is varied by adjusting the angle of attack of the foil. When not in use, the kite is stored in a garage, mounted on the fore deck. Kites seem to be very suitable for vessels which do not have the deck space to mount other systems, e.g., container ships or cruise ships.

All the systems are fully computerized, so that no extra crew are needed.

Hybrid, and purely wind vessels, will need to be designed to work with the sailing systems. The sails will stabilize the rolling motions of the vessel, but adequate stability must be ensured. In addition, the sails and underwater profile of the vessel must be balanced, to ensure there are no adverse steering effects.

5.1.4 Air lubrication

Air lubrication is a method of reducing the resistance between the ship's hull and seawater using air bubbles. The air bubble distribution across the hull surface reduces the resistance working on the ship's hull, creating energy-saving effects. With an optimized hull, the air lubrication system may achieve up to 10-15 % reduction of CO_2 emissions, along with significant savings of fuel.

The air lubrication works by trapping a layer of air bubbles beneath the ship's hull. Air bubbles are blown through outlets at different locations along the bottom of the hull, symmetrically on both sides of the ship's centre line.

The air is blown at a constant rate to form a layer of bubbles, which reduces the drag and resistance between the ship and the seawater. The system continuously replenishes the lost air bubbles ensuring that a uniform layer of air bubbles is maintained beneath the ship.

5.1.5 Energy saving devices

Energy saving devices are defined as different devices designed for optimising the flow to, around or after the propeller. The devices are primarily designed to alter the wake field or eliminate the losses arising on the propeller. Table 37 shows the working principle that the individual devices act to reduce, and Figure 42 shows how the devices may be combined, ref. (23).

Table 37 Working principles of various energy saving devices including individual saving potential

Working principle, reducing	Device	Saving potential
Rotational losses	Pre-swirl fins	3-5%
	Twisted rudder	1-2%
	Contra rotating propellers	4-7%
Rotational losses and separations in the aft body	Wake equalising duct	3-8%
Hub vortex losses	Efficiency rudders	2-6%
	Rudder bulb	2-5%
	Hub cap fins	2-5%
Tip vortex losses	Kappel propeller	3-6%

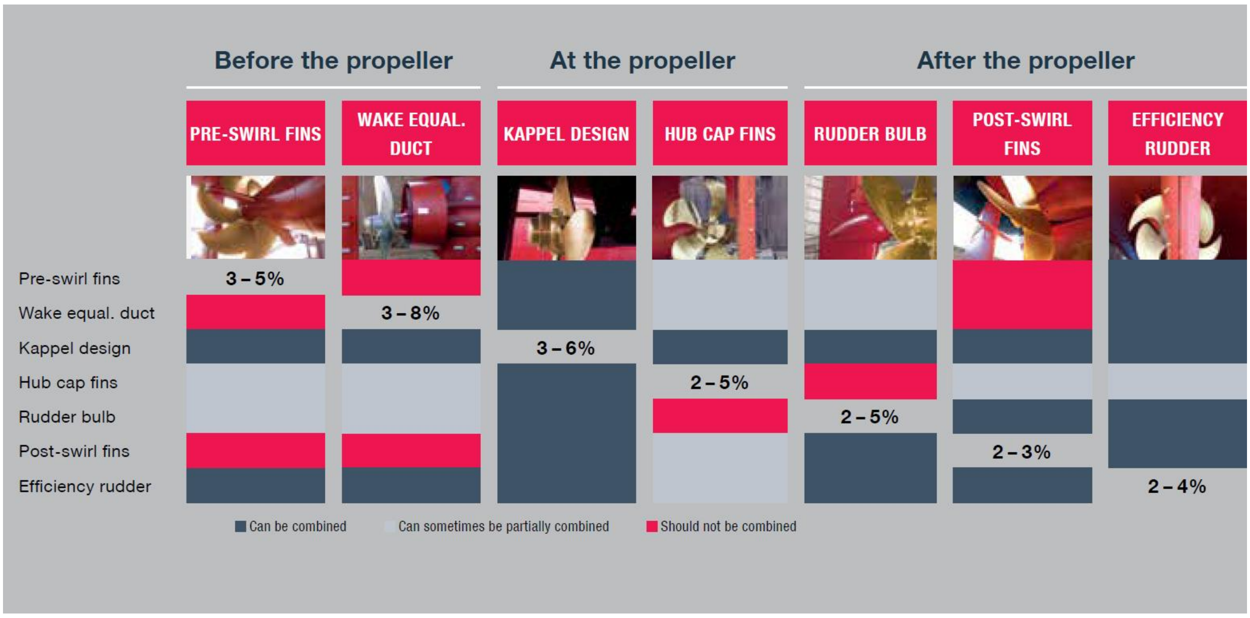


Figure 42 Possibilities for combining energy saving devices, including individual saving potential

It is important to note that savings cannot just be added, the devices act together as a system, and must be combined and optimized to get the greatest benefit. Experience has shown that these devices are unlikely to achieve combined savings of more than 10 % compared to a standard design.

The different devices also work best with different types of ship. E.g., Kappel propeller provides the largest savings for highly loaded (high C_{th}) propellers. The wake equalising duct (and similar duct systems) works best for ships with large block coefficients, as it equalises and reduces the wake fraction coefficient.

In general, hub vortex reducing measures (see Table 37), pre-swirl fins and twisted rudders provide rather simple, maintenance-free (other than cleaning) solutions and are amongst the most popular, ref. (23).

5.1.6 Anti fouling systems (AFS)

Marine fouling has a drastic effect on the power requirement, and therefore the emissions, of a ship. In extreme cases, calcareous fouling (barnacles and other hard growths), have been shown to increase the power requirement of a vessel by up to 86%, in order to maintain a speed of 15 kts, ref. (59).

The main purpose of an anti-fouling system is to hinder the fouling of the ship over time. However, there is an increasing trend, to incorporate friction reducing technologies in the anti-fouling, to reduce the ship's frictional resistance, and therefore emissions.

Traditionally, anti-fouling systems used biocides, poisonous substances added to the coating matrix to kill micro or macro-organisms that might settle on the hull, ref. (60). Due to increasing concerns about the biocides effect on the marine environment, laws and regulations on antifouling material compositions are becoming increasingly strict, so a lot of research and development is being done to develop non-biocidal anti-fouling systems. Also, at the present time, there are biocidal anti-fouling systems using low toxic or natural anti-fouling agents.

The most developed systems today are so called foul release systems, which work by minimizing the adhesive strength between the fouling organisms and the coating, so that the organisms are removed by hydrodynamical stress during navigation or by a simple mechanical cleaning.

Other, less developed technologies include:

Protein resistant polymers, which work by hindering the fouling organisms from attaching to the coating.

Conductive antifouling coating, which works by having an electrically negatively charged coating. Marine fouling organisms such as bacteria, polysaccharides, and natural organic matter commonly found in seawater, usually have negative charges, making them susceptible to electrostatic repulsion by a negatively charged surface.

Photodynamic antifouling which works by combining a non-toxic dye photosensitizer (PS) and harmless, low-intensity light to match the PS absorption peak that generates Reactive Oxygen Species (ROS), leading to intracellular biological molecules (lipids, proteins, and nucleic acids) oxidation. In most cases, microbial cell damage occurs in the cell wall, and the cells are penetrated, thereby selectively killing the microbial cells.

Biomimetic antifouling, which aims to replicate the anti-fouling properties of the skin/surfaces of marine animals, sharks, whales etc., or plants.

Along with the anti-fouling properties of the coatings, much research is being done to lower the ships resistance by the coating itself. Different manufacturers use different technologies, including:

The incorporation of a hydrogel in the coating, to give a water trapping function which lowers the hydrodynamic footprint of the hull.

The formulation of the coating to provide an extremely smooth surface.

The use of highly non-wetting, micro-patterned, or nano-patterned hydrophobic as a means of providing an air layer between the water and the hull, reducing the skin friction drag.

5.2 Fuel switch

The most common approach to generating power in the maritime sector is to use a diesel propulsion system. The applications of diesel propulsion systems are vast and can be found in almost all vessel categories with boats and recreational vessels. The following section in the report discusses alternative fuels that can be adapted to meet the zero CO_2 emission target in the maritime industry and the necessary changes required for the ship propulsion systems to accommodate the fuel switch.

5.2.1 Methanol

Methanol has been used in various applications and is commonly produced on a commercial scale from natural gas. Other options for methanol production are to use renewable resources such as biomass or electrolysis with green electricity and carbon capture utilization technology, ref. (61). Carbon emissions from green or renewable methanol would be considered climate-neutral because there will not be additional CO_2 emissions during the combustion than had previously been taken from it.

Methanol has a specific energy of 19.7 MJ/kg, which is much lower than hydrogen and conventional liquid fuels, ref. (61) and (62). Verhelst, et al., ref. (62) provide a comprehensive overview of methanol as a fuel for internal combustion engines. It has gained attraction over the past decades as an alternative fuel for diesel and gasoline for internal combustion (IC) engines. It is easier to store and handle than Liquefied Natural Gas (LNG), ammonia (NH_3), and hydrogen fuels (61). Renewable methanol in engines has achieved almost zero CO_2 emissions in recent years which is a great benefit over other fuels, ref. (63).

Methanol in engines can be in the form of pure methanol, blended fuel or dual fuel. Methanol is an excellent spark-ignition (SI) engine fuel due to its desirable characteristics such as high heat of vaporization, high flame speed, low combustion temperature, and low air-fuel ratio, ref. (64) and (62). SI engines require some engine modification however, those are not too significant. Due to high autoignition resistance, compression ignition (CI) engines need more significant modifications. The adopted duel-fuelling requires significant modifications to the fuelling system similar to the LNG conversion of such engines.

5.2.2 E-fuel

Electro fuels (E-fuels) are synthetic fuels manufactured using captured carbon dioxide or carbon monoxide together with low-carbon hydrogen. The term electro- or E-fuels comes as a result of using hydrogen that is obtained from sustainable electricity sources e.g., wind, solar and nuclear power. Further, it is a name for synthetically produced hydrocarbons that use renewable electrical energy, ref. (65).

Electro fuels could be a carbon-neutral alternative that enables the use of previously made investments in vehicles and fuel infrastructure. The production of electro fuels is carried out by mixing hydrogen and CO_2 in a synthesis reactor in which a range of liquid and gaseous fuels, including gasoline and diesel, can be produced, ref. (66). Nordic Electro Fuel (NEF) AS building Norway's, and perhaps the world's, first industrial and commercial production facility for e-fuel in Herøya, ref. (67).

5.2.3 Ammonia

Ammonia is an inorganic compound with nitrogen and hydrogen and does not emit CO_2 during combustion with oxygen. It also has been recognized as an excellent hydrogen carrier. To achieve the goals set by International Maritime Organization (IMO) to reduce GHG emissions, DNV suggested that by 2050 at least 15% of long-distance ships should be fuelled by ammonia or hydrogen. Machaj et al. ref. (68) provide an overview of ammonia as a potential marine fuel in various aspects. Several approaches are considered for the fuel switch such as to use of diesel engines with engine modifications and to use of Solid Oxide Fuel Cells (SOFC) as the source of heat and electricity in the maritime sector. Ammonia in CI engines as a single-fuel suffers from the requirement of extremely high compression ratios from 35:1 to 100:1. Other challenges that require engine modifications are high ignition temperatures, low flame temperature and low stoichiometric flame speed. Hydrogen Promoted Homogeneous Charge Compression Ignition (HCCI) engine for ammonia has been tested to improve the combustion efficiencies and engine stabilities, ref. (69). There are also suggestions to use waste heat from the combustion process to decompose ammonia partly into produce a mixture of ammonia, nitrogen, and hydrogen to mitigate the ignition difficulties, ref. (70).

Ammonia fueled SOFC is still in its early stage but has gained interest within the industry including the maritime sector as a method for zero CO_2 emission power generation. Rathore et al. ref. (71) discussed the progress and prospects of direct ammonia SOFC and highlighted several key areas to concern in SOFC. There will be a dilemma to use ammonia as a combustion fuel in diesel engines with required modifications or use ammonia driven fuel cell technology to power marine transportation. Available space in ships will be a crucial factor in making decisions. Accordingly, space for ammonia storage and energy generation must be estimated and compared with other alternatives.

5.2.4 Hydrogen

Hydrogen has the highest energy content per mass of all chemical fuels at 120.2 MJ/kg, which could increase the effective efficiency of an engine and lower the specific fuel consumption, ref. (72). Conversely, hydrogen has a low volumetric energy density that demands large space and low temperatures for storage.

It is possible to combust hydrogen in a diesel or a gas engine, ref. (73). There, hydrogen can be the sole fuel in the engines (mono fuel) or in a dual fuel system, ref. (74). For hydrogen as the sole fuel, the operational range in CI is limited due to the high resistance of hydrogen fuel to auto-ignition. A reliable ignition and smooth engine operation were observed after converting a diesel engine to hydrogen fuel operation with the assistance of a glow plug, ref. (75). For CI engines, the use of hydrogen becomes more realistic when it is combined with an additional lower autoignition temperature fuel e.g., diesel. Further, studies revealed that hydrogen-assisted diesel combustion resulted in a small increase in NOx emissions and a shift nitrogen oxide (NO)/nitrogen dioxide (NO_2) ratio making NO_2 the dominant component in some combustion modes.

Fuel cell technology enables a cleaner, more efficient, and perhaps the most flexible chemical-to-electrical energy conversion, ref. (76). Hydrogen as a fuel in Photon Exchange Membrane Fuel Cells (PEMFC) to produce electricity is widely discussed in the maritime sector. Many of the recent projects have looked into PEMFC due to its flexibility to apply in a large range of applications, ref. (77) and, ref. (78). Hydrogen-fuelled PEMFC demonstrates the efficiency of 40-60 %, high power density and operating conditions of 50-130 ^{0}C. The additional requirements for storage space due to low volumetric density, the need for bunkering and safe storage brings a negative impact on hydrogen as a fuel for the shipping industry, ref. (76) and, ref. (79).

5.2.5 Biofuel

Biofuels are synthesized from biomass or waste from other means hydrocarbons from biological sources using chemical and thermal methods, ref. (80). There are different paths for conversions of bioresources to synthesize gas such as anaerobic digestion followed by steam/dry reforming, fermentation, thermochemical (pyrolysis, hydrothermal liquefaction etc.), and gasification. Hydrogen from renewable energy sources is then combined with synthesis gas using a process of catalytic conversion to produce synthetic biofuels. There can be chemical variations in the products compared to conventional fuels such as gasoline or diesel but can also be used in diesel engines, ref. (81).

Other types of biofuels are FAME (fatty acid methyl ester), which is produced by the process of transesterification of vegetable oils, animal fats or waste cooking oils, and HVO (hydrotreated vegetable oil) also called HDRD (hydrogenation -derived renewable diesel) where the product comes through the process of fatty acids to-hydrocarbon, hydrotreatment of fats or vegetable oils-alone or blended with petroleum. As DNV reported, FAME is the most widely available type of biodiesel in the industry and is often blended with regular marine diesel. HVO/HDRD can be directly introduced to the existing diesel engines without any further modifications, ref. (81).

5.2.6 Nuclear

Nuclear marine propulsion has been a reality since the first nuclear-powered submarine USS Nautilus were launched in 1955 ref. (82). Since then, many navy vessels, sub-marines and surface vessels have been built and operated by USA, UK, Russia, France, China, Japan, and India. The majority have been and are submarines. The surface vessels include aircraft carriers and cruisers. About 700 reactors have been built for the purpose so far. According to world nuclear association there are more than 160 vessels with more than 200 reactors operating today, ref. (83). Several hundred vessels have over the years been decommissioned and is out of operation. Very few civil ships have been built, mostly Russian icebreakers.

The energy in the reactor is released by fission of uranium atoms (Isotope U235). The uranium is usually pellets of uranium oxide (for land-based power plants) that are arranged into tubes that form fuel rods. The fuel rods are arranged into assemblies for the reactor core. To be able run the fission reaction and capture the heat from it during operation the reactor core is immersed in a moderator media that slows down neutrons, normally "light" water or sometimes heavy water. In addition, there are control rods that can be inserted in between the fuel rods and absorb neutrons and slow down the fission reaction rate. The typical reactor used in marine propulsion is of the type Pressurized Water Reactor (PWR). In the PWR the core with fuel rods, control rods and water are within a pressure vessel of steel. The water is pressurized to 155 bars and will have a temperature of about 315 °C. This hot water is flowing in a closed loop top the steam generator. The steam generated is utilized in a steam turbine that drives either an electric generator or drives a propeller shaft for propulsion. The latter is different from what is the case with a land based nuclear power plant optimized for producing electrical power only.

Natural uranium contains 99.27 % of the isotope U238 and only 0.71 % U235. It is only the fission reaction of U235 that is sustainable and what is needed as fuel in the reactor. The U235 concentration is increased through an enrichment process to be able to make the fuel rods. Low Enriched Uranium (LEU) has U235 concentration between 0.71 % and 20 %. Highly Enriched Uranium (HEU) above 20 %.

Most commercial reactors run on 3-5 % U235 (reactor grade), ref. (84). Most naval reactors run on HEU.

Some special features for Naval nuclear reactors:

- The need to be small and is therefore run on HEU to be able to deliver high power from a smaller volume.
- Long core life so that time between refueling is above 10 years and up to several decades.
- Need to resist the forces experienced on a moving vessel at sea.

Typical information for reactor sizes is given as $MW_{electricity}$ (MW_{el}) or $MW_{thermal}$ (MW_{th}). Where MW_{el} is the electricity power output and MW_{th} is the heat needed from the core to run the steam turbine and generator. Typically, MW_{th} is 3 times the MW_{el} value.

For traditional large land-based power plants the MW_{el} is normally given and is for most reactors in the range between 500 -1 500 MW_{el}, ref. (85). The average is probably close to 1 000 $MW_{el.}$ with an efficiency 33 % this implies an average of 3 000 $MW_{thermal.}$ For naval reactors, the values are smaller.

According to the International Atomic Energy Agency (IAEA) many suppliers are working to develop micro sized or small modular reactors, ref. (86). IAEA has listed more than 70 reactors developments ongoing in 16 countries. Among these are 6 specifically for marine propulsion (Russia, China). In Table 8-2, some examples of naval reactors are compared to commercial land-based reactors and the smaller reactors under development.

Table 8-2: Example of sizes of reactors in some US ships/submarines compared to traditional land-based reactors and micro-sized and Small Modular Reactors under development. Ref. (87) (88) (89) (90)

Name of power plant or vessel	Type and model of reactor	Country	Displacement [tonne]	Ship length [m]	MW_{el}	MW_{th}	MW_{prop}
Ohio- class submarine	S8G (GE)	US	18 750	170		220	?
Nimitz – class Aircraft carrier	2x A4W (Westinghouse)	US	102 000	332	2x 100	2x 550	?
General R. Ford Class Aircraft carrier	2 x A1B (Bechtel)	US	100 000	N33	2x 125	2 x 700	2 x 260
Micro reactors	Several under development		N.A	N.A	Anticipated < 5 (1-2)	Anticipated <15 (5-15)	N.A
Small modular reactors (SMR) – Land based concepts under development	Several under development		N.A	N.A	Anticipated < 300 (60 -300)	Anticipated <1000	N.A
Typical land-based reactor today	Several		N.A	N.A	Average approx. 1000	Approx. 3000	N.A

To summarize; marine propulsion by nuclear power has been a reality and proven for more than half a century. Very few reactors and ships have been used for civil activity, the vast majority of vessels are naval submarines but also surface vessels like aircraft carriers.

The reactor types are specially adapted for ships and on fuel not available for civil purposes. They are small and powerful, using Highly Enriched Uranium above 20 % and up to >90 % U235 (US), not available for civil reactors.

As the basic principle is well proven and the fact that many development projects on SMRs and micro reactors are ongoing, it is quite likely that nuclear reactors can be developed as an alternative to fossil fuels, on civil ships, in a decade or more. One example of research projects aiming for this is the Norwegian project "Nuclear Propulsion of Merchant Ships 1" or NuProShip 1, ref. (91). (Planned to be continued with NuProShip 2 and 3).

France, one of the leading countries in nuclear power generation, want to have their first land based SMR in operation within 2030, ref. (92).

In addition to the technical solutions and cost there are issues related to regulations, operation, safety, waste and decommissioning that need to be solved for worldwide civil use of nuclear-powered ships. Current IMO regulation is "Code of safety for nuclear merchant ships" Resolution A.491 (XII) adopted on 19 November 1981. The regulations include many aspects of the adoption of nuclear merchant marine propulsion. It also indicates the need for update of regulations as the technology progresses. Due to security, safety, and environmental risks the use of nuclear energy is regulated through international legal and national framework. The International Atomic Energy Agency (IAEA) plays an important role in developing treaties and seeking wide adoption between member states. A review of treaties is probably needed for widespread use of nuclear marine propulsion.

5.2.7 Electrification and battery

Electric motors for ship propulsion exist today both for civil and naval purposes. Electricity is produced by a combustion engine or nuclear reactor driving a turbine and generator to produce the electrical power for the electrical motor. Huge ships as the cruise ship "Symphony of the Seas" are operated like this with total diesel engine power at 96 MW and total motor capacity for propulsion at 82 MW, ref. (93).

Widespread utilization of battery all-electric ship propulsion is currently limited to relatively small or medium sized ships with short routes. Battery-electric ships have all the energy stored in the battery, and in recent years many short ferry routes e.g., in Norway have gone all-electric. Typical range of battery size 1-4 MWh. The challenge with electric battery propulsion is the need for relatively frequent charging. This is possible when the route is short and the infrastructure for rapid charging is in place. Table 8-3 gives some examples of ships and battery capacities. Hybrid electric/diesel is an alternative for larger ships.

Battery systems offered for large ships is in the range up to 50 MWh (94). The batteries are intended for zero emission for in/at/out of port, regulated areas (cruise in fjords), prevention of blackout, peak-shaving and load leveling.

Table 8-3: Examples of ships with all-electric propulsion (95) (96) (97)

Ship name	Type	Propulsion	Dead weight	Battery capacity	Sailing route
MF TychoBrahe	Ferry	All- electric or back-up with diesel	2 500	4.16 MWh	Helsingør-Helsingborg
MV Yara Birkeland	Container	All-electric (autonomous)	3 200	6.8 MWh	Herøya- Brevik
Bastø Electric*	Ferry	All-Electric or Diesel or hybrid		4.3 MWh	Horten-Moss

*Charging system Bastø Electric 9 MW (max), regular charging 7.2MW

Recent Life Cycle Analysis (LCA) of electric battery propulsion for ships emphasize that the source of electricity is essential for the environmental impact of the technology compared to conventional propulsion by fossil fuels, ref. (98).

There are several potential environmental factors that need to be considered in an LCA. Global warming, acidification, eutrophication, abiotic depletion, ozone depletion, and photochemical oxidant creation. A switch from fossil fuels to all-electric battery propulsion can affect all or several of these factors, but the impact depends heavily on the source of electricity.

For climate the global warming is the most important factor and is governed by the total greenhouse gas emissions. According to The Norwegian Water Resources and Energy Directorate (NVE) the electricity produced in Norway in 2021 had a CO_2 factor of 11 gCO_2eq/kWh power delivered (the climate declaration for physically delivered electricity). The EU countries have in comparison approx. 300 gCO_2eq/kWh, ref. (99). Countries that have a very high fraction of electricity based on fossil fuel will typically have values in the range 400 – 750 gCO_2eq/kWh. Examples are, South Africa, Poland, Australia, India, and China. The above mentioned LCA analysis conclude that an all-electric battery vessel operated at the coast of e.g. Australia, China, India and Poland, relying on the domestic highly coal based electric-power production, will have an overall negative GWP impact compared to a vessel operated purely with diesel, ref. (98).

For countries relying on a high fraction of renewable or nuclear power production, it will be a clear positive impact on global warming with all-electric battery powered vessels.

5.3 Onboard CO_2 capture

Onboard CO_2 capture in ships has got the attention of several maritime companies. Mitsubishi Heavy Industries (MHI) investigated the feasible ways to install a carbon capture and storage unit on a very large crude carrier, ref. (100). Recently, a consortium of global shipping organizations and the Oil and Gas Climate Initiative (OGCI) got Approval in Principle (AiP) from the American Bureau of Shipping (ABS), the US ship certification agency, to use a carbon capture system onboard an oil tanker. This aims to demonstrate the feasibility of using carbon capture onboard a vessel, ref. (101). UK's Department for Transport granted funds to PMW Technology to analyse their A3C carbon capture process for marine exhaust gases. The process captures CO_2 from exhaust gases by freezing, then subliming the CO_2, ref. (100). Naval architect company, Houlder Ltd. works as the marine consultant in the project, ref. (102). Other companies such as Wärtsila and TECO 2030 develop scrubbers to reduce SO_x, NO_x, and PM to facilitate future CCS activities in ships. In the EverLoNG project, a project co-funded by the ERA-NET Accelerating CCS Technologies (ACT3) initiative, ship-based CO_2 capture

(SBCC) is to be demonstrated at TRL 7 by the end of the project. The CO_2 capture technology is amine-based capture (MEA) and the demonstration unit is to be installed and tested on two different vessel, a Total Energies owned LNG tanker (LNG fueled) and Sleipnir a crane vessel owned by Heerema Marine Contractors (LNG and MDO fueled) with the goal of reaching TRL 7, ref. (103).

There are several challenges in implementing a CO_2 capture system on a ship. The freedom is limited especially in using the space compared to an on-land facility. For stability requirements, the height of columns is a critical factor, ref. (104). The capture process requires energy both in the form of heat and electricity. This energy needs to be supplied by onboard energy sources on the ship. It is possible to recover some heat from the ship engine exhaust, but it is alone not sufficient to fulfill the thermal energy demand of an amine-based absorption-desorption process to operate at above 50 % CO_2 capture efficiency with 30 % MEA as solvent. The study performed under the CO2LOS II project suggested using a fuel afterburner to provide extra heat to achieve 90 % CO_2 capture efficiency. This will increase fuel consumption by 6-9 % for LNG and 8-12 % for diesel as fuel sources. To capture 70 % of CO_2 from the exhaust at specific reboiler duty of 4 MJ/kgCO_2 and 30 % MEA as the solvent, ships with LNG as fuel requires an absorber column with 20 m of packing height and ships with diesel as fuel requires an absorber column with 12 m of packing height. The CO_2 concentration from LNG and diesel engine exhausts are 3.6 vol% and 4.8 vol%, respectively. The increase of CO_2 concentration from diesel engine exhaust is the main reason for the reduction of required packing height between the two alternatives. To operate the absorber column at a minimum energy penalty, the estimated packing height would be approximately 20 m that resulting in a total absorber column height of more than 30 m, ref. (105).

A study conducted by Luo and Wang, ref. (106) emphasized that integrated CO_2 capture process into the ship energy system including marine diesel engines and steam turbines could reach a maximum of 73 % of CO_2 capture efficiency. The study shows the possibility to increase capture efficiency by up to 90 % by introducing an additional gas turbine and fuel consumption to provide the extra energy to the CO_2 capture process.

Membrane-based onboard CO_2 capture and liquefaction have been investigated for LNG-fueled ships (107). Such a capture process could potentially be easier to installed and more compact compared to the amine-based technology. In ref. (107), the energy consumption for the membrane alternative was found to be more energy intensive than the amine-based approach. Future development could potentially make the membrane alternative more attractive if the selectivity of the membranes increases.

A clear benefit of capturing CO_2 from a CO_2 cargo ship is that at the time it comes into operation, it is already integrated into a CO_2 handling system, meaning that it should be possible to unload it at a suitable location.

The CO_2 that is captured onboard needs to be compressed and stored intermediately until the CO_2 can be unloaded for permanent storage. Further investigation into optimal condition for storing the captured CO_2 onboard a CO_2 cargo ship is needed as this will likely depend on several factors, like associated energy penalty, transport length (CO_2 volumes to be stored), and potentially the CO_2 infrastructure to which the CO_2 is unloaded. Even though the CO_2 is captured onboard a CO_2 cargo ship it might not be feasible to store the captured CO_2 in the CO_2 cargo tanks used for CO_2 transport. The feasibility of this will depend on the condition of the CO_2, pressure, temperature, and purity achieved for this CO_2. Onboard storage space should be estimated based on the capture during the voyage in which 1 tonne of liquified CO_2 needs about 1 m^3 of space, ref. (100). In ref. (108), the effect of three different storage pressures for SBCC on the space needed for storing the capture CO_2 onboard.

6 DISCUSSION

With the potentially imminent implementation of shipping into the EU ETS, the time is becoming critical for implementation of low and zero emission technologies. At least initially, the focus will likely be on technologies that can be implemented on existing ships within a few years. One such technology could be onboard CO_2 capture, however the relatively low TRL of onboard CO_2 capture and the lack of significant CO_2 handling infrastructure will limit implementation. It might be that some of the alternative fuel options could be implemented, especially the fuel types that can use the engine types already installed. Here, however, limiting factors will likely be fuel production rates from sustainable sources, as Scope 2 emissions from fuel production will need to be accounted for, and fuel supply infrastructure. Further, other negative aspects related to HSE (health, safety, and environment) must be assessed before implementation.

The greatest emission reduction while still utilizing traditional fuel types, may be done with a combination of wind assistance, air lubrication, anti-fouling systems, energy saving devices and engine efficiency improvement.

If zero emission is to be achieved, it is clear that a combination of different technologies needs to be implemented and ultimately it might also entail purchase of CO_2 offset credits.

Low emission shipping on the other hand should be achievable either through onboard CO_2 capture, ship optimization and especially implementation of wind assistance technology, and fuel-switch (assuming that the fuel is generated from sustainable sources) alone.

WP5 – ROADMAP TO UNMANNED FSI

1 INTRODUCTION

In this work package a roadmap for an unmanned FSI is developed. The work is based on the report "SBM Offshore Contribution to WP 5 Unmanned FSI - Main Subjects to Consider", ref. (4) (Appendix A), which was originally focused an unmanned FPSOs. The WP5 report explains the FSI concept and evaluates the applicability of the FPSO analysis from the SBM report. Further the concept of unmanned facilities and the motivation behind is discussed. Maturity of the technological solutions and the associated regulations are listed in the roadmap. The roadmap is used to define a Design Basis for an unmanned FSI, ref. chapter 6.

2 THE FLOATING STORAGE AND INJECTION UNIT (FSI) CONCEPT

2.1 FSI Description

The term FSI is used within the CCS terminology as a short form for a Floating Storage and Injection Unit.

When a CCS case encompasses ship transport and injection of CO_2 to an offshore storage reservoir, an FSI may be considered as a part of the logistics chain. The FSI will be permanently located at the offshore injection site. The main purpose of including an FSI is to provide continuous injection into the reservoir. This is considered more favourable for the reservoir behaviour and will also increase the utilization of the well. The FSI should fulfil the following main functions:

- Receipt of liquid CO_2 from a CO_2 transport ship
- Interim Storage of liquid CO_2
- Pressurizing and heating CO_2 to the state needed for injection
- Continuous CO_2 injection via risers connected to the wellhead
- Metering of injected volume
- In order to provide these services, the FSI should be equipped with the following features:
- A floating hull
- Cargo tanks for liquid CO_2
- Process plant for CO_2 conditioning
- CO_2 transfer system connecting the FSI to the ship during loading
- CO_2 transfer system permanently connecting the FSI to the wellhead
- Station keeping system
- Supporting systems such as power supply, control systems, etc

In CO2LOS II, WP4, ref. (109), the concept of a CO_2 offshore storage and injection unit was discussed and evaluated. As a part of this evaluation a selection tree was developed. When utilizing this selection tree for an FSI (per definition a floating concept) and assuming the required storage volume exceeds 15 000 t, relevant concepts are either a Sevan Unit or a Ship-Shaped Unit, ref. Figure 43.

Figure 43 - Sevan and Ship-shaped Unit

In WP4 of ref. (109), a ship shaped manned FSI with a storage capacity of appx. 30 000 m^3 was developed to an early conceptual stage.

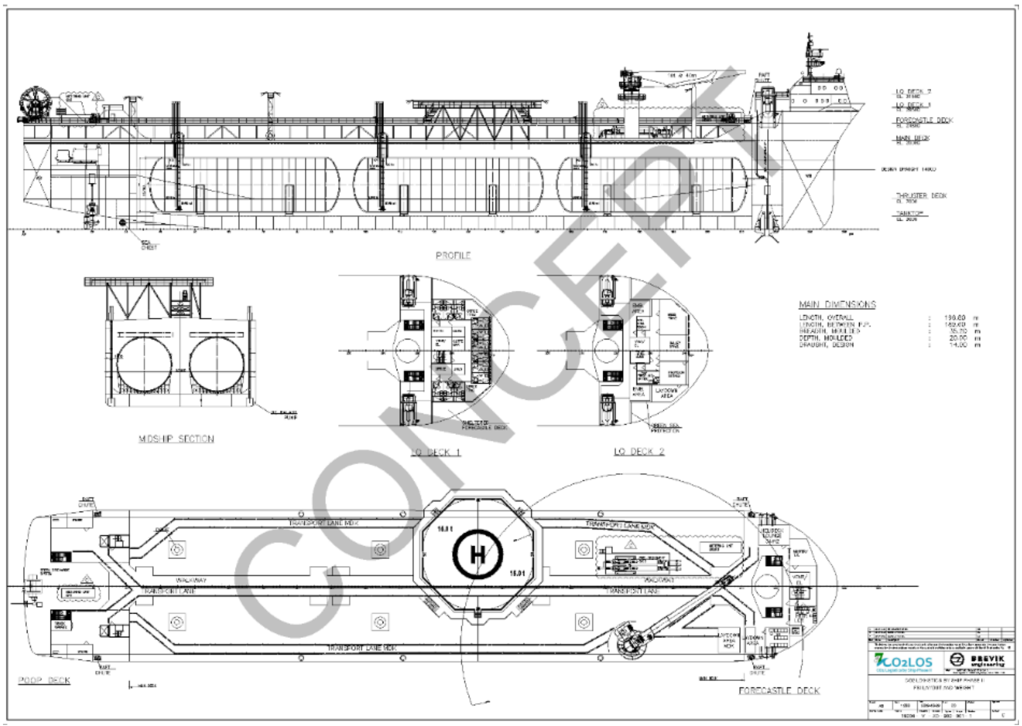


Figure 44 - FSI early concept, ref. (109)

2.2 Similarities with the FPSO concept

Although the flow is in the opposite direction on an FSI compared to a traditional FPSO, the main functions are comparable:

- Floating installation permanently located at offshore location
- Displacement hulls suited for storage of large volumes of cargo
- An onboard process plant
- Exchange of liquid with regularly arriving ships
- Position keeping
- Risers connecting the unit to the wellhead

As of today, there are no FSIs in operation, under construction or detailed beyond an early conceptual stage while FPSO units are well known and proven concepts dating back to the mid-seventies and with hundreds of units in operation. A main strategy of this document is to make use of available relevant

FPSO information and experience in general and in particular the part which is related to unmanned FSPOs, when developing the roadmap and design basis for an unmanned FSI.

3 UNMANNED INSTALLATION

3.1 Definition

When considering the concept of an unmanned installation, the level of human involvement needs to be clearly defined. The following categories are normally used:

Not Normally manned – allows for manning during planned maintenance campaigns, planned operations such as loading and unloading and unscheduled corrective maintenance. Also allow for permanent manning of facilities for remote operation of the unit.

Unmanned – allows for unscheduled corrective actions and permanent manning of facilities for remote operation of the unit

Autonomous – allow only for unscheduled corrective actions

When selecting the category "unmanned" it calls for the elimination, in normal activity, of onboard personnel. In order to achieve this technically, the facility design has to incorporate unmanned into the functionality. This can be achieved by an increased level of automation and autonomous sequences eliminating manual tasks. In addition, this has to be combined with increased reliability and durability of equipment and systems to reduce interventions from an operations and maintenance perspective, ref. (4) (Appendix A).

3.2 Motivation

The below items listed in ref. (4) are the main motivation for developing an FSI without manning:

- Increased Safety – inherently safe, removal of humans from dangerous offshore environments
- Reduced Risk – reduction in human error by utilizing automation, artificial intelligence, and robotics, etc
- Increased Efficiency – improved uptime, predictive approach, harnessing the power of data, improve mean time to failure and intervention
- Reduced Cost – OPEX reduction, decrease in salaries, logistics, spare requirements, etc
- Decarbonization – reduce carbon footprint of the asset and operation

4 ROADMAP TO UNMANNED FSI

In ref. (4) a roadmap for the transition from a fully manned FPSO via a minimally manned, an unmanned and finally an autonomous unit is described. Most of the identified gaps to be filled are also relevant for an FSI. Based on the findings in ref. (4) (Appendix A), a roadmap describing the transition of a manned FSI to an unmanned facility is made. This roadmap does not go via the minimally manned concept, nor does it lead to full autonomy. Also, FPSO specific gaps is disregarded and FSI specific gaps included. The roadmap is shown in Figure 45.

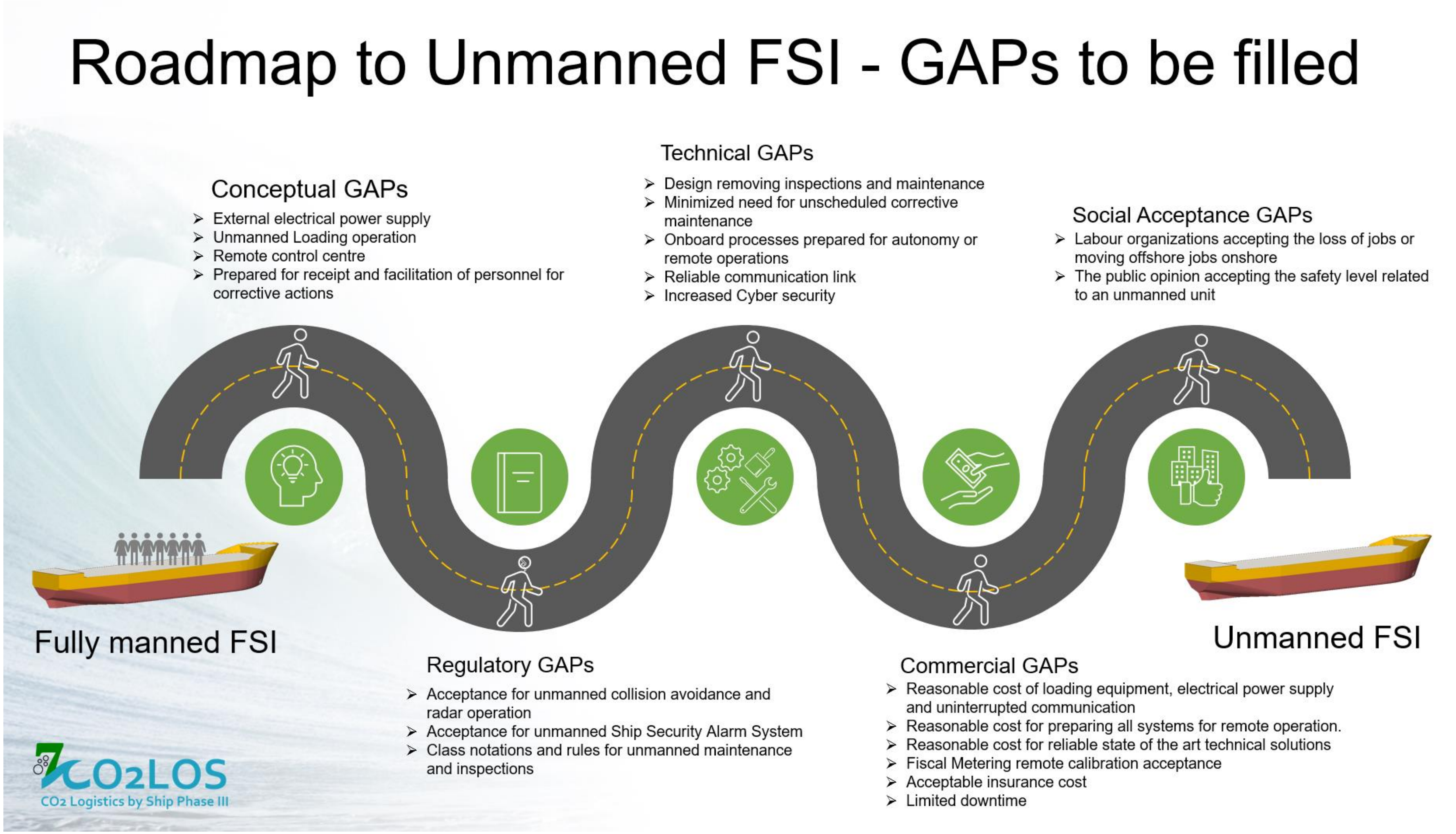


Figure 45 - Roadmap to unmanned FSI

5 GAP DESCRIPTION

The GAPs listed in this chapter are primarily items described more in detail in the SBM report, ref. (4) (Appendix A). Here they have been categorized in five categories.

5.1 Conceptual GAPs

These GAPs are major functions of the installation needed to be developed for unmanned operation

5.1.1 External electrical power supply

The FSI should be supplied with an uninterrupted electrical power supply from an external power source. This to exclude the need for onboard combustion engines. Electrical engines are generally less maintenance intensive and more reliable compared to combustion engines.

5.1.2 Unmanned Loading operation

Connecting the loading hose to the shuttle tanker is, to a large degree, a manual process. It is a frequent operation that requires a lot of manpower.

5.1.3 Remote control center

The target is not full autonomy of the FSI. As defined in chapter 3.1 an unmanned installation may be remotely controlled from a control center. Such a control center should be established with uninterrupted connection to the FSI.

5.1.4 Prepared for receipt and facilitation of personnel for corrective actions

The FSI should be prepared for taking onboard personnel from a support vessel, typically of walk to work design. Also, the facility needs to be prepared for safe operation of the personnel when onboard.

5.2 Regulatory GAPs

In general regulations for FSI's are not fully developed. This will however not be the focus here. Identified GAPs will be between regulations for manned and unmanned FPSO excluding those related to hydrocarbons. The GAPs are either missing regulations for unmanned operation or regulations directly in conflict with the unmanned concept. GAPs are limited to the FSIs operational phase at the injection site, i.e., unmanned transit or disconnection in severe weather is not considered relevant. During operation the FSI will be subject to shelf state national regulations, flag state requirements, IMO requirements, and Class Rules.

5.2.1 Acceptance for unmanned collision avoidance and radar operation

IMO has issued the International Regulations for Preventing Collisions (COLREGs) requiring manned collision avoidance and radar operation. This must be dispensed with for an unmanned installation.

5.2.2 Acceptance for unmanned Ship Security Alarm System

IMO Resolution MSC.136 requires manning for implementing a Ship Security Alarm System (SSAS). This system requires activation from the navigation bridge. This must be dispensed with for an unmanned installation.

5.2.3 Class notations and rules for unmanned maintenance and inspection

It is not required with Class on a permanently moored offshore installation. However most floating ship-shaped units maintain Class during operation. The condition of the FSI hull, machinery, cargo system, mooring and anchoring system and safety system will be monitored by the Class, normally by use of manned inspections. New Class notations allowing a scheme for unmanned inspections must be developed.

5.3 Technical GAPs

These GAPs are the main technical issues that need to be solved to facilitate an unmanned installation.

5.3.1 Design removing inspections and maintenance

A main challenge is to increase the reliability and robustness of all technical installations including structural items and coatings, removing the need for personnel performing planned inspections and maintenance within the lifetime of the facility. Necessary inspections and maintenance will have to be carried out autonomously or by remote control.

5.3.2 Minimized need for unscheduled corrective maintenance

This item also relates to an increased level of reliability and robustness.

5.3.3 Onboard processes prepared for autonomy or remote operations

All onboard processes that cannot be eliminated by design, need to be prepared for either working autonomously or by remote control. Sensors connected to analytic tools processing the acquired data shall be installed to support the processes and the operators.

5.3.4 Reliable communication link

A reliable communication between the FSI and the remote control center is required. There are several alternatives further described in ref. (4), ch.7.1.

5.3.5 Increased Cyber security

Measures to ensure Cyber Security have to be applied to the main control and safety system, preventing hostile take-over of the facility.

5.4 Commercial GAPs

These GAPs are related to items that might increase the CAPEX and/or OPEX of the installation beyond the commercially acceptable. Also, the ability of the concept to attract investments may be considered a possible commercial GAP.

5.4.1 Cost of loading equipment, electrical power supply and uninterrupted communication

Depending on the concepts selected to mitigate these items, CAPEX investments may rise considerably.

5.4.2 Cost of preparing all systems for remote operation.

As an example, all valves must be actuated with signal interfaces and software for remote control. Preparation and maintenance of a digital twin may be required and add to the CAPEX and OPEX cost.

5.4.3 Cost of reliable state of the art technical solutions

Investing in technical solutions (equipment, tanks, hull, instruments, etc) that will not require manned inspection or maintenance will cost more than standard solutions.

5.4.4 Fiscal Metering remote calibration acceptance

Fiscal metering equipment for oil and gas on the Norwegian shelf requires frequent calibration (110). There is reason to believe this would also apply to CO_2. Acceptance of remote controlled calibrations must be given. This must also be solved technically.

5.4.5 Acceptable insurance cost

There is a risk that insurance costs will be higher for an unmanned installation until reliability is proven by years of continuous operations without incidents.

5.4.6 Limited downtime

The introductory phase of an unmanned concept will likely involve a high degree of downtime due to novel technology. This will impact the revenues created by the unit.

5.5 Social acceptance GAPs

Although all relevant rules and regulations may be fulfilled, the public opinion and non-regulative organizations may have objections to an unmanned installation.

5.5.1 Labor organizations accepting the loss of jobs or moving offshore jobs onshore

Historically, when oil companies operating in Norwegian sector have moved tasks and employees from attractive offshore jobs with 2 weeks on and 4 weeks off rotation to land based jobs with more regular work hours, labour organizations have protested. Protests are also likely if the jobs are eliminated, however less so for a new unmanned unit compared to converting an existing unit from manned to unmanned.

5.5.2 The public opinion accepting the safety level related to an unmanned unit

The FSI will not handle hydrocarbons, but there is substantial skepticism in the public opinion when it comes to uncontrolled emissions of CO_2.

6 DESIGN BASIS FOR AN UNMANNED FSI

The design basis describes a fictitious floating storage and injection unit (FSI) for operation in the Norwegian Sector of the North Sea. The FSI shall operate as an unmanned unit with remote operation from a manned control center. Design Measures to fill the GAPs to unmanned operation identified in the "Roadmap to Unmanned FSI" are introduced as a part of the Design Basis.

6.1 CCS case framework parameters

A framework for the FSI project is given by a set of parameters listed in Table 1. The choice of parameters is based on experience acquired earlier in the CO2LOS projects. These parameters should be regarded as an example for a feasible CCS case. Other parameters may be selected for an actual project. Although a low pressure design is selected, a reasonable margin to the triple point is applied due to the unmanned philosophy. Also, the relatively strict CO_2 specification from Northern Lights is selected in order to minimize the risk for corrosion.

Table 38 – CCS case framework parameters

Description	Value
Injection site location	The North Sea in Norwegian Sector
Injection site Water depth	100 - 200 m
Injection site Significant wave height	Max 15 m
Batchwise or continuous injection	Continuous
CO_2 parcel size (arriving ship cargo capacity)	40 000 t
CO_2 transport operating pressure	8 barg
CO_2 transport mechanical design pressure	9.5 barg
CO_2 injection rate (max)	250 t/h
CO_2 injection delivery pressure	160 bara
CO_2 injection delivery temperature	5°C
CO_2 specification	Northern Lights, ref. (1)

6.2 FSI main design features

A ship shaped hull is selected for the FSI. This is also the most commonly used hull shape for FPSOs. Due to the harsh environment at the selected injection location, a weather vaning mooring solution is needed. A retractable submerged mooring buoy is selected. A swivel allowing for receipt of CO_2 and utilities and delivery of CO_2 to the injection well shall be installed in the mooring buoy. The storage capacity of the FSI is chosen on the basis of the cargo capacity of the arriving vessel and a preliminary estimation of the surplus volume needed to provide continuous injection to the well in the case of delayed delivery from the ship. A detailed logistics analysis must be done in a later phase. The hull dimensions are governed by the required storage capacity. Other limitations may apply when the building yard is selected. As discussed in ch.5.1.1, power supply from external electrical cable is preferred for an unmanned installation.

Table 39 – Main design features

Description	Value
Hull	Ship-shaped
Mooring	Submerged buoy allowing the unit to weathervane
Cargo and utilities transfer	Through swivel in submerged buoy
Installation lifetime	20 years
Storage capacity	48 000 m^3
Power source	Electrical supply from shore

6.3 FSI features for unmanned operation

The main GAPs for unmanned operation are closed by introducing the features listed in *Table 40*. Reference is made to descriptions in the SBM document, ref. (4). Unmanned loading operation is further described below.

Table 40 – Features for unmanned operation

Description	Value
Power supply	HVDC electrical cable from shore, ref. (4), ch.8.
Unmanned Loading operation	Ship to FSI connection, ref. ch.6.3.1
Remote control	From onshore control centre, ref. ref. (4), ch.6.2
Receipt and facilitation of visiting personnel	Connection with W2W vessel, ref. (4), ch.9.
Unmanned collision avoidance and radar operation	Remotely operated system, ref. (4), table 13.2
Unmanned Ship Security Alarm System	Remotely operated system, ref. (4), table 13.2
Unmanned maintenance and inspection	Ref. (4), ch.12
Processes prepared for autonomy or remote operation	Ref. (4), ch.5
Communication link	Fibre cable from shore, ref. (4), ch.7.1-3
Cyber security	Increased Security, ref. (4), ch.7.4
Fiscal Metering	Remote calibration and operation ref. (4), ch.4.3

6.3.1 Unmanned Loading Operation

A manned FSI may execute the connection and cargo transfer operation with a shuttle tanker in a similar manner to that of an FPSO, although the liquid flows the opposite direction. Shuttle tanker loading operations currently require manning on board the FPSO to connect the loading hose, monitor tanker/FPSO motions and weather conditions. Normally a pick-up line is manually shot over with an air gun to the forecastle deck of the tanker, so the offloading pipe and mooring hawser can be pulled over to the tanker. Connection to an unmanned FSI may require transfer of tanker crew to the FSI for hose connection, ref. (4) table.13.4. This is not in line with the Unmanned philosophy, ref. ch.3.1. An alternative solution is shown in Figure 46. Here the arriving shuttle tanker connects to a mooring and cargo transfer system. This system is connected to the FSI via a cargo pipeline and a submerged buoy mooring and riser system.

This system will allow for unmanned operation of the FSI, however it comes with an additional investment cost compared to a conventional tandem loading system. Also, risers suitable for low temperature transfer of CO_2 and operational procedures needs to be developed.

The design basis is summarized in Figure 46.

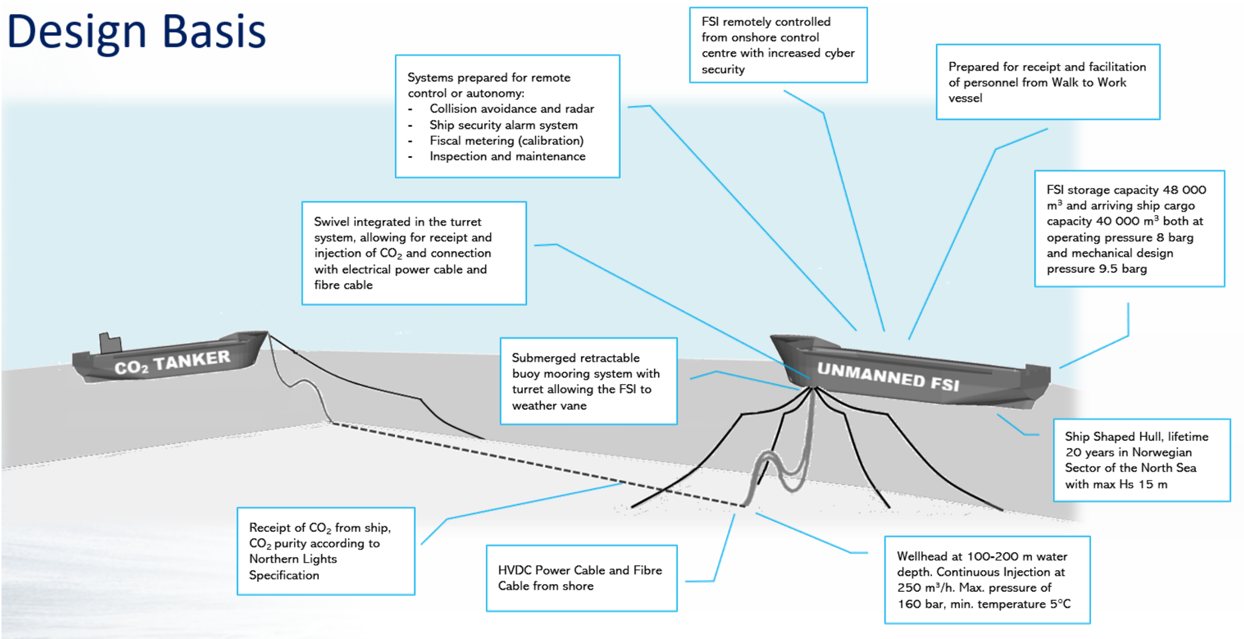


Figure 46 – Design basis

WP6 – POTENTIAL FOR BATCHWISE INJECTION

1 INTRODUCTION

Work Package 6 attempt to identify if there are any major showstoppers for batchwise injection of CO_2. The work has been carried out by researchers in SINTEF and Brevik Engineering AS with input from the CO2LOS partner IMODCO and the company CarbonCollectors. A literature study has been undertaken and workshops and meetings have been arranged. All partners in CO2LOS were invited to the workshop 9th of January 2023.

1.1 Scope

Following up findings from the previous CO2LOS II project, ref. (7) where the need for continuous CO_2 injection was highlighted as an important issue for ship transport of CO_2. In a future scenario, ships may collect CO_2 from sources at ports or at offshore locations, and transport to a CO_2 receiving injection facility. If there are no possibilities for intermediate storage or by other means of achieving a constant CO_2 injection flow rate the opportunity for periodic CO_2 injection should be explored further.

WP 6' objective in the CO2LOS III project is to outline the potential for batchwise CO_2 injection. The main tasks are:

Investigate the possible showstoppers for batchwise CO_2 injection
Overview of new research/opportunities

The result of WP 6 is this report showing the potential for batchwise CO_2 injection and highlighting the showstoppers for such an arrangement.

1.2 Method

A literature review with the aim of finding similar periodic CO_2 injection processes in use for other applications has been executed. The literature covering CO_2 – EOR is extensive and probably the largest base of experience for periodic CO_2 injection. This concept consists of a cyclic injection of CO_2 to increase production by lowering oil viscosity and promote miscible displacement of oil. However, the CO_2 - EOR process is not intended for permanent storage which is the main focus in the CO2LOS III project. Several permanent storage locations are in operation today and have been so for many years now. Published material from the Snøhvit-, Sleipner and In Salah fields have been investigated and the experience should be transferred to a future batchwise injection facility's design- and operational procedures. The main showstoppers for batchwise CO_2 injection found in literature are discussed and the potential mitigation measures are listed based on:

- Workshop with the company Carbon Collectors and partners
- Discussions/meetings with project partners
- Discussions within SINTEF

2 STATUS OF CO_2 INJECTION TODAY

As there is no previous experience with deliberate batchwise CO_2 injection for permanent storage, the aim of the literature review has been to identify similar applications. For CO_2 storage projects in operation worldwide today the aim has often been a continuous CO_2 injection. Even if the aim is continuously injection, the design of the well should take into account about possible interruptions due to seasonal variations, various maintenance or modification tasks, well tests, workovers and treatments, equipment failures, weather conditions or intermittent CO_2 supply, ref. (5). This experience is important to collect and keep in the knowledge base when discussing deliberate batchwise CO_2 injection.

Several studies focus on pressure control and optimizing storage efficiency under intermittent CO_2 injection conditions. During WAG operations with supercritical CO_2, ref. (111) found pressure increase during water injection and steady pressure during CO_2 injection. Experience from CO_2-EOR projects using water alternating gas (WAG) show a tendency to lose around 20% injectivity over the lifetime of a well, ref. (111). Maintaining a constant injection rate will require an increase in injection pressure over time and may result in a risk of reaching the fracture pressure. Composition Swing Injection (CSI) where CO_2 rich fluids of different CO_2 mole content are injected in series to avoid pressure build up are reported as a promising technology. Ref. (112) investigated constant-, stepwise incremental-, stepwise decremental and cyclic CO_2 injection which showed a reduction of pressure build up during cyclic injection. Even though the published WAG studies support an outcome of reduced pressure build up during alternating gas injection this was not supported by extensive research of this phenomena in literature, ref. (5).

Simulation results of six CO_2 – brine injection cycles with water unsaturated with CO_2 show differential pressure increase during cycles with both CO_2 and brine injection. Fluid mobility is controlling the differential pressure in the test set up and this is assumed to be influenced by pore space geometry, wettability characteristics and residual saturation of each fluid phase ref (111). Results show that periodic CO_2 injection may result in an increase in residual trapped CO_2. Increased residual trapping within the same pore space would utilize the space more efficiently and save cost on monitoring a smaller reservoir volume with a highly dense CO_2 distribution. More CO_2 left in the pore space close to the injection well by increased residual trapping will potentially increase the injection pressure for water as the water needs to displace CO_2.

Simulations of batchwise injection of CO_2 (without water injection between batches of CO_2) performed in, ref. (5) showed promising results with regards to improved injectivity (compared to first batch) reduced pressure increase and improved storage capacity. Evaluation of challenges from case to case is necessary to mitigate risk of serious consequences from periodic CO_2 injection and optimization of such.

Enhanced Oil Recovery (EOR) or tertiary oil recovery method is extraction of oil which would not have been extracted without use of these methods. Typically, recovery can be increased to 60% of original oil in place with tertiary methods compared to 20% for primary recovery and 40% for secondary recovery techniques. The three main types of EOR are:

Chemical flooding
Miscible displacement
Thermal recovery

According to ref (113) the first CO_2 related EOR project was initiated in 1958 in Oklahoma, US and the first large scale commercial CO_2 EOR project started operations in 1972 at the SACROC field in West Texas, US. This was still operating in 2021.

CO_2 injection is part of the miscible displacement category in which CO_2 and crude oil can mix to form a single homogeneous phase. Cyclic CO_2 injection, also called "huff and puff" is often referred to in US EOR-CO_2 projects ref (114). Cyclic operations of CO_2 injection for EOR purposes have been successfully carried out for many years. Injection of CO_2 is often followed by a shut-in period allowing for CO_2 diffusion and dissolution processes. These processes result in oil swelling and increased saturations and a reduced viscosity which all improve overall oil recovery.

In addition to huff 'n puff CO_2 can be applied in continuous flooding- and Water Alternating Gas (WAG) flooding for EOR. CO_2 can also be applied in Enhanced Gas Recovery (EGR) as pressure support in natural gas reservoirs preventing subsidence and water intrusion. CO_2 injection into deep coal beds for methane extraction, enhanced coal bed methane recovery (ECBMR) has been in operation as well according to, ref. (113).

Both huff 'n puff and CO_2 WAG are technologies with well proven intermittent CO_2 injection. However, these are not optimized for maximizing permanent CO_2 storage, ref. (5).

Temperature variation and low temperatures may affect the exposed wells during CO_2 injection compared to conventional production. Strong temperature variations are especially frequent in discontinuous CO_2 injection operations, ref. (115). Temperature variations may potentially cause expansions or contractions of well casings and barrier materials which may result in cracks or loss of bonding at interfaces and reduce the fracture pressure and thereby reduce CO_2 injection capacity ref (116). Mapping the individual safe operational envelope of the temperature variations is of major importance. There are negative effects associated with intermittent CO_2 injection as well. Geochemistry may potentially play a role during periodic CO_2 injection including changes in fluid- and rock composition and properties. This may result in salt precipitation, hydrate formation risk and bacterial growth. The risk and consequence of such formation damages depend on variables such as initial conditions, induced compounds or bacteria during well activities prior to injection, temperature and pressure variations and the injection rate of CO_2.

A search among ongoing and past CCS projects reveals that CO_2 is not necessarily continuously injected. This is due to required maintenance, well- tests, workovers, and stimulations. At the Snøhvit CO_2 injection facility, CO_2 is separated from the hydrocarbon gas and further purified before injection into a saline aquifer. Figure 47 below shows longer periods without CO_2 injection into the Tubåen formation of the Snøhvit field. This is due to various maintenance and operational issues. The pressure build-up in 2008 from Figure 47 resulted in a shut in as the injection pressure reached the estimated fracturing pressure.

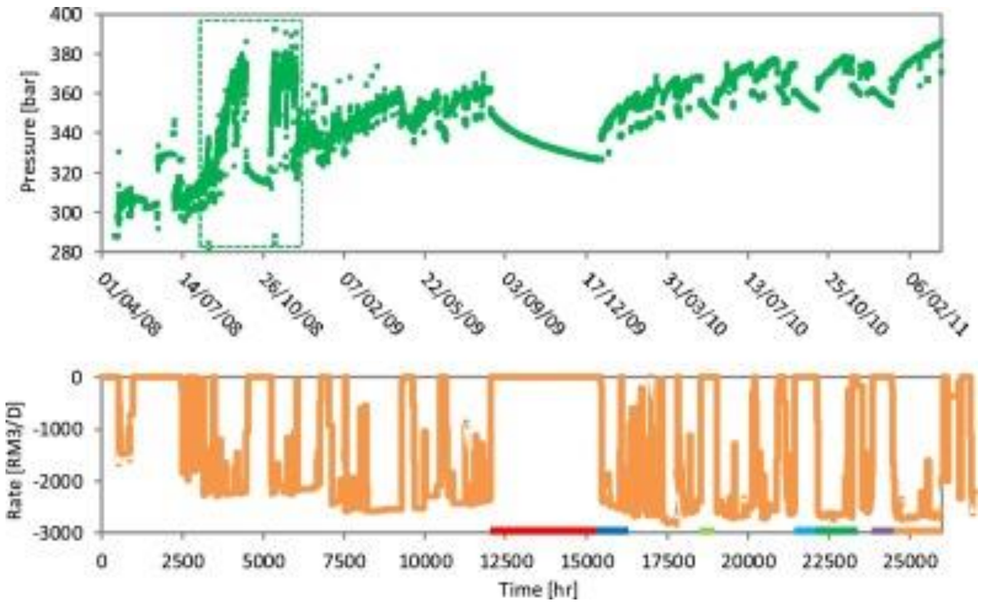


Figure 47: CO_2 injection pressure and rate into the Tubåen formation, at the Snøhvit field ref (5)

A reduced permeability of the rock in the near well region may induce problems for CO_2 injection and storage. Undesired pressure build-up and fracturing in the near well area may create severe injectivity challenges. Dry CO_2 injection into a reservoir may cause water surrounding the injector to evaporate and result in salt precipitation. Intermittent CO_2 injection can cause back flow of brine phase during shut-in periods and consequently affect salt accumulation in the near well area. Salt precipitation is governed by various parameters such as composition of the water phase, residual water saturation, injection/flow rate, pressure and temperature. Injecting CO_2 at high pressure and low temperature favors solubility of carbonate materials and may potentially increase injectivity. During the shut-in periods the temperature may increase, and pressure decrease. This can lead to less carbonate solubility and more precipitation and injectivity problems at start up, ref. (5).

Hydrates may form when injecting CO_2 at low temperature and high pressures. The risk of hydrate formation depends also on the water and gas compositions. Hydrate formation in the near well area can lead to injectivity problems. Hydrate inhibitors are often used during start-up and shut down activities in Oil & Gas operations when the risk of entering the hydrate formation region is likely. This tool can be implemented for batchwise CO_2 injection operations as well.

For the Tubåen reservoir at the Snøhvit field CO_2 is separated onshore from the well hydrocarbon stream and transported by pipeline to the offshore injection facility and into the storage reservoir, ref. (117). The CO_2 injection has been periodic at Snøhvit, see Figure 47. In 2008 there was a lower injection than expected, and an unanticipated pressure increase was seen. The pressure increase was assumed to be caused by salt precipitation which reduced the injectivity. A weekly MEG (Monoethylene glycol) injection campaign was initiated and after several treatments the injectivity increased to expected level. As the CO_2 is dried onshore to avoid corrosion issues in piping and process components and injected into a sandstone formation it was assumed the formation dried out and increased the salinity in the residual water and eventually caused salt precipitation. During a large turnaround in 2009 and shut in for 3 months, the pressure decreased but increased quickly up to pre-turnaround levels shortly after startup.

Material and operational choices are different in the three well-known CO_2 injection and storage projects, Sleipner, In Salah and Snøhvit. CO_2 cools down when arriving in the Sleipner reservoir and warms up in both In Salah and Snøhvit. CO_2 injection at Sleipner is done with wet CO_2 compared to the others as they inject dry CO_2. During long shut-in periods at Sleipner, the temperature and pressure falls within the hydrate formation region and hydrate inhibition must be utilized. CO_2 is in the phase transition area at the well head on Sleipner and liquid for the In Salah and Snøhvit fields. At In Salah the decision was made to dehydrate the CO_2 to avoid corrosion instead of installing stainless steel in well completions according to, ref. (118). There are companies today specializing in well construction for CO_2 injection applications. Cement, bonding and material technology are all important factors for reducing the risk of batchwise CO_2 injection failure.

3 BATCHWISE INJECTION EFFECT ON OFFLOADING /INJECTION

3.1 Offloading /injection

There are several technologies and systems for offloading the CO_2 from the ship, and the choice of system will be different according to weather conditions, water depth etc. There are two main concepts, either direct injection from the ship to the well where the conditioning and injection equipment is placed on the ship or offloading from the ship to a platform/floating facility where the conditioning equipment is located, and injection is performed. Both solutions have their pros and cons, however ship transportation gives batchwise offloading either way. In CO2LOS II, it was suggested two options for direct injection offloading systems: Single anchor loading (SAL) system and submerged turret loading (STL) system. The SAL system is compatible with a bow loading system (BLS) that can be integrated to the ship. The BLS is flexible and can be used for offloading to multiple sources. The STL system could also be a suitable solution as it does not require disconnecting in harsh weather. However, it is a more expensive solution both when it comes to initial investment and that it requires more space onboard the ship ergo a bigger ship is needed.

3.2 Tower loading unit: CO_2 injection TLU

In the CO2LOS project, one of the partners, IMODCO, has provided information about their CO_2 injection TLU (Tower loading unit). The CO_2 injection TLU will be used in the Storage part of the Carbon Capture and Storage (CCS) value chain from the company Carbon Collectors, which aims to serve a logistic chain for CO_2 handling. It is based on the well proven concept of a weathervane turntable mounted on a fixed structure via a roller bearing. The turntable is fitted with a hawser to safely moor a barge (filled with CO_2 in liquid phase) and extends with a boom structure supporting a hose catenary to be connected to the barge bow manifold (see Figure 48). On the balancing side of the boom structure, there is a platform to host the injection pumps sized for the project specific requirements. This scheme allows to re-allocate most of the assets to different reservoirs – and therefore this “virtual pipeline” could also be used in the first phase of a project – de-risking the pipeline investment cost.

Figure 48 Schematic drawing of a tower loading unit (TLU)

3.3 Pumps

An injection pump to increase the pressure from ship transport condition to the design well head condition for supplying the required injection rate is needed. In addition, a seawater pump is needed to pump the sea water from the sea to the heat exchanger if heating of the CO_2 is required. The cold CO_2 in the ship tanks is first pumped to the desired pressure (for example 80-130 barg, depending on the injection pressure) before heating to the desired temperature. The project has investigated the size of such pumps, and with a flow rate of 115 kg/s of CO_2, and a pressure increase from 8 to 120 barg, the power demand for both of these pumps is 1517 kW. During the pressure increase, a temperature rise of around 7° C is foreseen, if the inlet temperature of the CO_2 is -50°C.

3.4 Heat exchanger

If the ship contains cold CO_2 (-28°C or -50°C), heating is required. The heat exchanger could be installed on the ship or at the terminal loading unit. As the heat requirement is significant, it would be beneficial to use a sea water heat exchanger to lift the temperature from minimum -50°C to 0°C. The project has investigated the size of such heat exchangers, and an example is given below. It should be mentioned that the assumptions may change according to sea water temperature, pressure required etc, but this shows the needed area for a certain amount of CO_2 to be heated from -53°C to 0°C. The energy required for heating will be drastically reduced if the CO_2 is around -30 compared to -50° C. The calculated example is based on unloading and injection of 10 000 ton CO_2 per 24 hours (116 kg/s).

Other assumptions are:

- CO_2 temperature increased from -53°C to 0°C in a heat exchanger with sea water as heat source.
- Sea water temperature in = 5°C, Sea water temperature out =2°C
- Overall heat transfer coefficient = 3000 W/m^2K

Results of the calculation shows a heat duty of the heat exchanger (HX-1) of approx. 10.5 MW. The cold CO_2 flow 1 (at -53°C, 8 bar) has been pumped in C-1 (E3 energy input approx. 1.6 MW) and thereby enters HX-1 as flow 3 with increased temperature and pressure (-45°C, 120 bar). The sea water flow 6 (5°C) and flow 8 (2°C) is 830 kg/s (Pump energy is approx. 0,45 MW). Calculated heat transfer area is 1853 m^2. The total of input of power is then approx. 12.5 MW, including the 2 MW of electrical power needed for the pumps. Figure 49 illustrates the concept of heating the CO_2 by a heat exchanger.

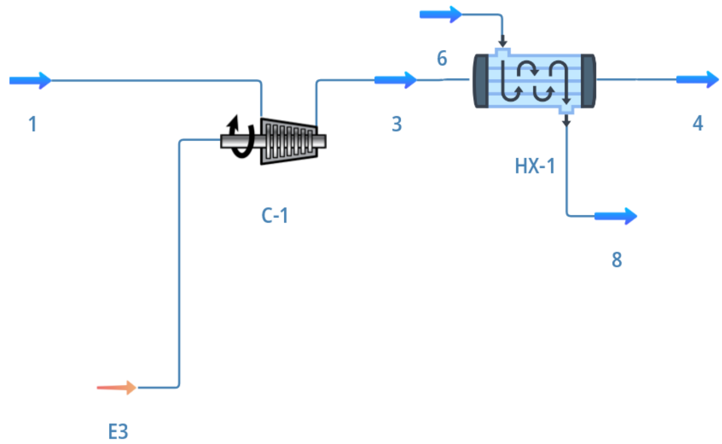


Figure 49: Cold CO_2 (stream 1-3-4) heated by a pump (C-1) and a heat exchanger (HX-1) with sea water (stream 6-8)

4 BATCHWISE INJECTION EFFECT ON WELL

4.1 Effect on well completion integrity

Temperature variations in the well are among the identified challenges for batchwise injection. Large and repeated temperature variations are mentioned as a possible threat to the integrity of the well. CO_2 injection in batches will increase the temperature variations compared to a more continuous injection. The compressed and cooled CO_2 is much colder than the rock formations surrounding the well. At the start of an injection, the temperature will therefore drop in the injection well until it stabilizes (steady state) after a given time. After the end of the injection, the temperatures will start to rise again until it, if given enough time, reaches the temperature of the surrounding rocks. Both the well and the surrounding bedrock will be affected, and the temperature fluctuations will be largest near the wellhead. The frequency between and duration of injections are important parameters determining the temperature fluctuations.

Completion of a well is done to avoid leakages and to secure operation during the lifespan of the well. The completion consists of several layers of different materials. Steel pipes of different diameters are used as casings. The casings are fixed with cement in the annulus between casings and bedrock and between casings. Several studies show that it is difficult to maintain the integrity of the cement. In Figure 50, ref. (119) two examples of completion of wells are shown.

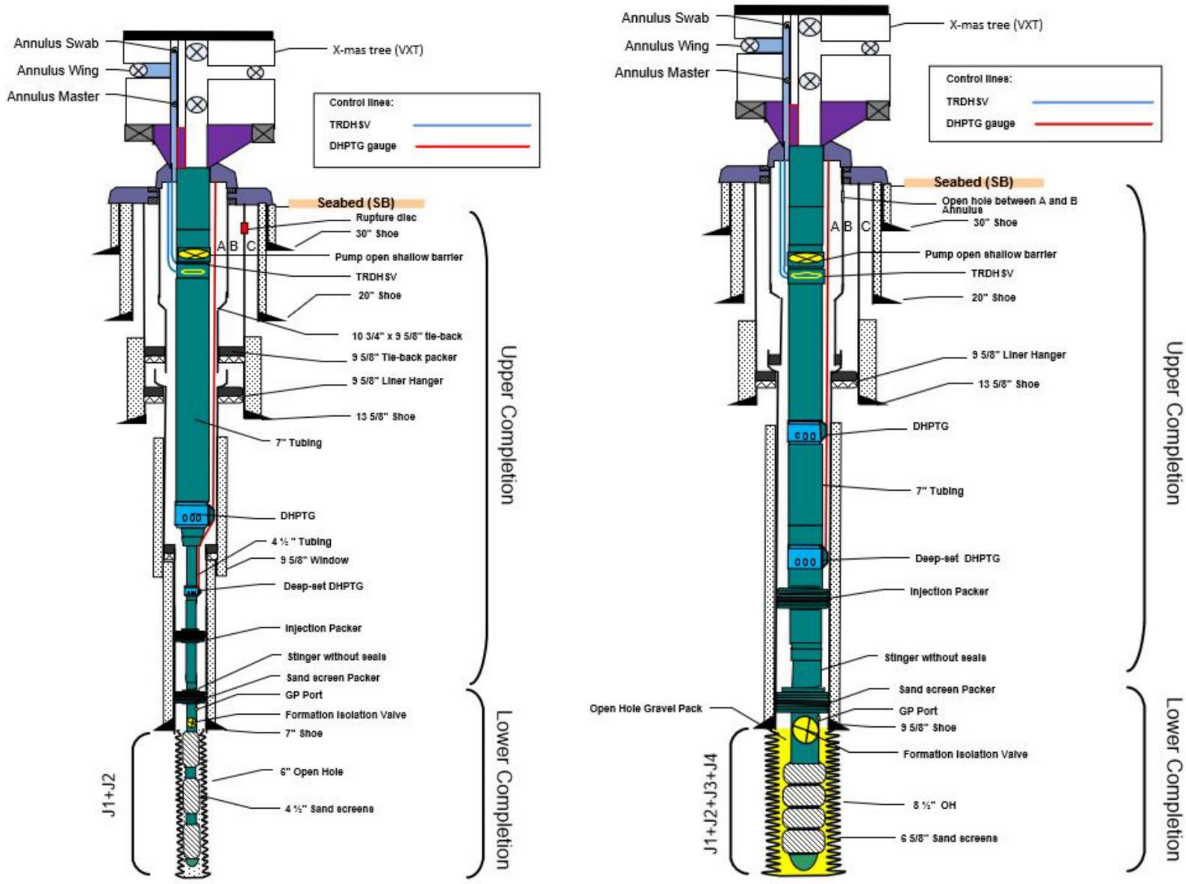


Figure 50: Example of the complexity of injection wells, Northern Lights, ref. (119)

The steel, cement and rock formations have different linear coefficients of thermal expansion (CTE). Typical CTE value for steel casing is 13x 10^{-6} /K and for oil well cement, somewhat lower at water saturated state; 9x 10^{-6} /K, ref. (120). CTE values for the rock formation depend on the minerals present. As the temperature decreases when injection of cold CO_2 starts, the core of the inner steel casing will contract and create stress on the surrounding cement annuluses.

Recommendations on how to design, drill, complete and operate a CO_2 injection well have been given in, ref. (115). The recommendations include Material and fluid choices for well construction, cement placement, safe temperature range and operational parameters. Some studies have done both simulated experimental work on cyclic temperature variations (temperature range -50°C to 80°C) to study the impact on well integrity, ref. (116)). The results indicate that radial cracking of cement may occur during the heating stage, while debonding may occur in the cooling stage. Others (ref (121)) also simulated the effect of temperature in the casing/sealing interface with alternative materials to the cement. The materials included a polymer, sand slurry, Portland Cement and Bismuth-tin alloy. Temperature gradients where highest using polymer and lowest using bismuth-tin.

The conclusion is that a sealant material with higher thermal conductivity will minimize the temperature gradients thereby lowering the risk of debonding.

4.2 Well temperature limitations and cold CO_2 heating demand

As described in 4.1, temperature fluctuations may be a threat to the integrity of the injection well. This applies both when cooling down as CO_2 injection starts and continues to steady state, and when it is heated again during shut-in periods, as will be the case with batch-wise injection. As the rock formation has a relatively high temperature (geothermal gradient in the North Sea is typically between 30 and 35 °C/km), it would be beneficial if the CO_2 that is injected is not very much colder than the surroundings. Low temperatures in and near the well can also cause problems due to frost and hydrate formation. CO_2 temperature and mass flow rate are critical parameters.

In a ship transport case with low pressure CO_2, the temperature of the CO_2 at top side is very low, at -53°C, if no heating is applied. Simulations, ref. (122) show that the CO_2 temperature going from the ship down through the riser and pipeline in seawater, further down into the injection well will increase, but that this temperature increase is not sufficient to avoid very low temperatures when entering the well head (total length of riser and pipeline 1 km). This especially applies if pipelines and risers cannot transfer heat directly to seawater, e.g. if an insulating layer of ice is forming or if the pipeline is buried in the seabed/mud. If icing can be avoided and the pipeline is exposed directly to seawater, heat will be exchanged with the sea, but this is probably not sufficient. A top side heating is probably necessary. Such heating requires a significant energy consumption, which must be supplied from ships or loading buoys at the unloading point.

To quantify the energy need at the topside heater or heat exchanger the complete system should be simulated with riser, pipeline lengths, materials, CO_2 mass flow, well materials, well depth etc. Temperature limits for the different sections or zones need to be set, based on expected problems that might occur due to low temperatures.

Certain criteria for injections have been proposed in, ref. (122):

- Avoid ice formation due to freezing of seawater on the outer surface of riser and pipeline. Minimum temperature on riser and pipeline outer surfaces > -1.9°C (Freezing of sea water)
- Avoid hydrate formation near the bottom of the well. Minimum temperature in the bottom hole formation > 10-12°C
- Avoid freezing of tubing/casing and near formation with risk of cracking and loss of material integrity in cement and surrounding rock formations.

The heating requirement will then depend on what temperature that can be tolerated in the liquid CO_2 at the top of the riser and the following sections of pipeline and well. A HYSYS simulation, ref. (122). of a CO_2 flow of 275 kg/s, at -53°C (8 bar), show that approx. 12MW heating and 4 MW pumping power is needed to bring the temperature up to -23°C (126 bar) and that an additional 13.5 MW is needed to bring the temperature up to 0°C (124 bar). The total power demand is estimated to be 29.5 MW. Alternatively, if the CO_2 storage temperature on the ship is -20°C (20 barg) the energy for heating is significantly reduced. 7.4 MW heating and 3.6 MW pumping power (total 11 MW) is needed to bring the temperature to 0°C (118 bar). Energy consumption is then only 37% for the case starting at -20°C (20 barg) compared to the case starting at -53°C (8 bar), when the goal is 0°C (approx. 120 barg).

Utilization of any excess heat on the tanker should be considered for a heat exchanger for heating the liquid CO_2 and before an additional heater is applied. This in combination with heating through the pipeline in seawater will limit the need for extra energy. In section 3.4 the possibility of using a sea water-based heat exchanger is described in connection with the loading unit.

5 BATCHWISE INJECTION EFFECT ON THE RESERVOIR

Several options exist for permanent storage of CO_2 in the subsurface, most considered are deep saline formations (aquifers), depleted oil and gas fields and coal seams. Several examples of CO_2 storage in aquifers and depleted gas fields exists (pilots and commercial projects) and we therefore only consider these in the following.

Storing in oil and gas fields gives the advantage of a confirmed sealing formation and often a good knowledge of the subsurface geology after decades of production. However, oil and gas fields are penetrated by a number of wells from the exploration and production phase representing a leakage risk as status of these legacy wells can be uncertain. Global total storage capacity of depleted oil and gas fields are considered to be much less than for aquifers.

Aquifers have an estimated global storage capacity of between 1000 GtCO and 10000 $GtCO_2$, ref. (119), which is more than required for the future scenarios of decarbonisation to reach the climate goals in the Paris agreement. A drawback of using saline formations is that a significant amount of mapping and exploration of the target formations are required before they can be used, which takes time and can be expensive. Even with a formation being well characterised before injection start, it's capacity and performance cannot be fully known until after injection has commenced.

5.1 Depleted gas fields

Using depleted gas fields for storage gives, as mentioned above, some significant advantages compared to aquifers. The geology, sealing properties and capacity (assuming re-pressuring the field to initial pressure) of the reservoir is known. It might also be possible to reuse some of the existing infrastructure which may lead to cost savings. If that is the case, the material and structure should be able to handle the new conditions involving CO_2, which might be different to the conditions of producing natural gas.

Storage capacity for CO_2 in a depleted gas field will strongly depend on the reservoir pressure after depletion. In fields with an active aquifer the depleted reservoir pressure can after some time be close to initial pressure while fields with less or no aquifer support may have depleted reservoir pressures as low as 20 bar giving a potentially large pressure margin for safe storage. For comparison, oil fields are mostly produced by pressure support from water injection to give a high recovery, leaving the depleted reservoir close to or at initial reservoir pressure regardless of aquifer support.

Injecting CO_2 in depleted gas reservoirs with low pressure raises some challenges. Large pressure drops along the process flow can be present both in the well (especially at start-up and stops) and when the CO_2 enters the reservoir. A decrease in pressure will cause Joule-Thomson cooling which in extreme cases could result in freezing in the well and near well region causing injectivity and potentially also integrity problems. A reduction in temperature of the injected CO_2 in the reservoir, due to the Joule-Thomson effect, to below 10°C could form hydrates with the residual water present in the reservoir. Hydrates could also form in the well if the water content in the CO_2 is high (not dry

CO_2), see Figure 51. Formation of CO_2 hydrates can cause severe blocking in the well and in the reservoir.

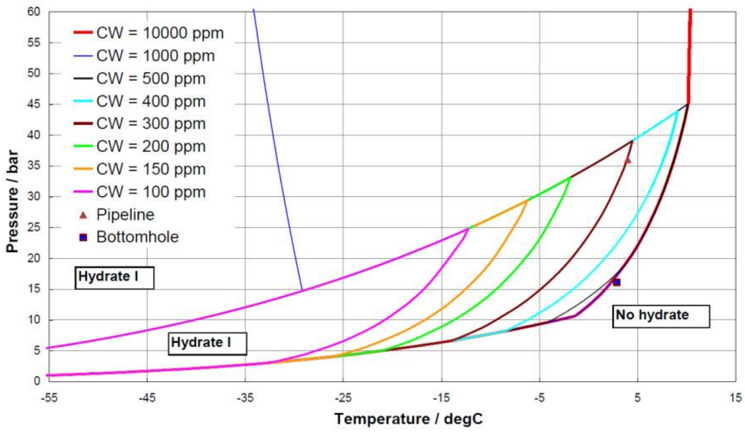


Figure 51 Hydrate formation curves for CO_2 with different amounts of condensed water (not dry CO_2), ref. (123)

Combination of the cooling effect and batchwise injection gives cyclic temperature fluctuations potentially causing debonding between casing and cement and radial fracturing of the well cement as discussed earlier (section 4.1).

A basic assumption for CO_2 storage in depleted fields is that the structure can be re-pressurised to initial pressure conditions. However, the change in strain and stress in the reservoir and sealing formation during depletion may have weakened the seal (and formation) and the actual safe pressure increase could be lower than assumed. Geomechanical modelling should be performed to investigate this for each case.

Salt precipitation could be an issue also when injecting in depleted reservoirs since residual water will in most cases be present in the reservoir also in the hydrocarbon zone. The problem of salt precipitation is discussed further in the next section. One of the main showstoppers for injection of CO_2 in depleted fields is the number of legacy wells posing a leakage risk. However, legacy wells are considered a risk regardless of if the injection is continuous or batchwise so we do not consider these here.

5.2 Aquifer Storage

Most large scale CCS projects to date have used saline aquifers as storage formations, as they are well suited for storing the CO_2 if there is a sealing cap rock above. Contrary to pressure depleted gas fields the aquifers selected for CO_2 storage are usually at hydrostatic pressure conditions unless affected by neighbouring activity (e.g. oil and gas production or other subsurface activity). Thus, the problems from strong Joule-Thomson cooling caused by the low pressure at the bottom of the well is not present. However, effects of cyclic temperature fluctuations caused by batchwise injection of cold CO_2 is still present (mostly close to the well head), but to a lesser degree. An example of typical temperature variation along the well for batchwise injection of CO_2 at 5°C injection temperature is given in section 6 below.

Injecting CO_2 into a reservoir at hydrostatic conditions requires a bottom hole pressure (BHP) in the well that is higher than the reservoir pressure. The pressure difference between the well and the reservoir is required for pushing the CO_2 into the formation. Pressure in the well between the batches will reduce as the injection stops and the BHP will equilibrate to the (new) reservoir pressure. However, this will be a relatively slow process (minutes/hours, depending on injectivity) and large temperature effects from this pressure decrease is not anticipated.

Results from, ref. (6) indicates that batchwise injection can have beneficial effects on both storage capacity and injectivity by increasing residual gas trapping (hysteretic effect) for each cycle. However, after a number of cycles this effect will reduce and injectivity will be comparable to the constant injection case with a low water saturation in the near well area.

For aquifer storage of CO_2, injectivity problems can be caused by salt precipitation which is expected to be a bigger problem for batchwise injection, compared to continuous injection, since stopping injection will allow water to re-imbibe (flow back), increasing the total salt content in the near well region. This problem can be remediated by injection of fresh or low salinity water to push the salt away from the well or MEG treatment can be used as in the Snøhvit field. Injectivity problems arising from hydrate formation can be a problem if the temperature of the injected CO_2 is below 10°C when it enters the reservoir (injection of cold CO_2). If hydrate problems are anticipated, MEG injection is typically applied to avoid these. Backflow of CO_2 and water into the well should not be a problem in aquifer storage as long as the pressure at the well head are shut in between loads (requires a well head closing valve), i.e. the BHP in the well should not be reduced to values below the near well reservoir pressure between loads.

6 INJECTION TEMPERATURES QUANTIFIED

During this work, a presentation made by the company Carbon Collectors was given to the project. They have investigated the temperature concerns often quoted for batchwise injection. As a design limitation, they have only investigated ship transport of CO_2 at approximately 5°C. They have also focused on depleted gas fields in the southern part of the North Sea. Three different models for their investigation have been used: CO_2 analytical Well model, OLGA and CO_2 analytical Reservoir model. The case investigated, assumes that the ships arrive quite often, only 4 hours between the ship injection as it is essential to utilize the wells as much as possible due to their high costs.

Below is a table showing the tubing head pressure (THP) and temperature (THT) at the top of the well and the bottom hole pressure (BHP) and temperature (BHT) at the base of the well from a modelled injection. Figure 52 lists the temperature and pressure at the start and end of a 22.5 hours injection period for the cases where the well has had a 56 hours injection stop (case 1, no injection and the temperature stabilizes) and after a 4 hours injection stop (case 3). The 4-hour injection stop (case 3) is used as an estimate of time from flow stopping at end of ship unload to start of flow from new full ship. Temperature and pressure at the top and bottom of the well at the start-up and after 22.5 hours injection is listed.

Case	THP (bara)		BHP (bara)		THT (°C)		BHT (°C)	
	0 hr	22.5 hr	0 hr	22.5 hr	0 hr	22.5 hr	0 hr	22.5 hr
(1)	22	59	42	204	1	-6	125	37
(3)	23	57	48	204	1	-6	78	34

Figure 52 Injection temperature and pressure modelled

Restarting after 56 hours or 4 hours did not change the minimum temperatures since the top of the well is almost back at ambient temperature after 4 hours. Observe that the bottom hole temperature (BHT) fluctuation is twice as large (88°C) during the injection after a 54 hour stop compared to after a 4 hour stop (44°C).

The minimum temperature the steel tubing could be exposed to in these simulations, is caused by immediately re-starting injection following an unplanned trip, near the end of an off-load period, and this results in a minimum temperature of -17°C. Inhibiting a restart for about 30 minutes reduces this to -15°C, which is the minimum temperature the steel tubing will see on a normal end of off-load shut down. This temperature reduction on shut down only effects the top 40% of the well, the remainder of the well remains broadly on its temperature profile. The figures below show the temperature profile in the period after shutdown of injection (up to around 30 minutes). The different curves show the time between 22h and 22.5h, and the minimum reached temperature is about -17°C at the top of the well.

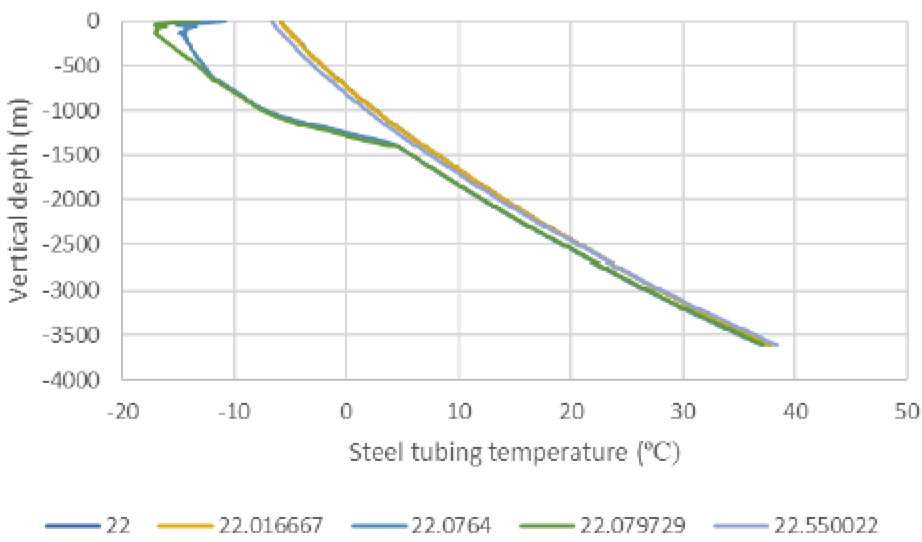


Figure 53 Temperature profile in the well

The temperature variation will need to be part of the design specification, but at this stage it is not believed to be unfeasible, although this work remains to be done. The temperature range exposure is not expected to be materially different for dense phase continuous injection schemes (depending on well depth, reservoir temperature and depletion pressure). The main difference is the number of cycles/fatigues which will need to be incorporated into the design specification.

7 SUMMARY AND CONCLUSIONS

The main task of this report is to identify if there are any major showstoppers for batchwise injection of CO_2. No such major showstoppers have been identified, but there are some challenges that needs to be addressed due to frequent shutdowns and related temperature changes in the well and reservoir. Some of the challenges presented below are very case specific and may only pose as a showstopper if it is a certain type of reservoir, very long disruptions in the injection flow or specific temperature ranges for the CO_2. The list of potential showstoppers does not include all aspects with batchwise injection, but it gives a good overview of main challenges that should be taken into account when considering batchwise injection of CO_2:

7.1 Temperature variation

Large and repeated temperature variations are mentioned as a possible threat to the integrity of the well and there are reports which state a significant span in the wellbore temperature between each CO_2 injection cycle. Temperature variations may potentially cause expansion or contractions of well casings- and barrier materials and rock deformation which may result in cracks or debonding at interfaces and reduced injectivity. Mapping the individual safe operational envelope of the temperature variations is of major importance. For depleted gas fields used for CO_2 storage, a combination of the cooling effect and batchwise injection gives cyclic temperature fluctuations potentially causing debonding between casing and cement and radial fracturing of the well cement. For aquifers, some literature, ref (5) indicates that batchwise injection can have beneficial effects on both storage capacity and injectivity by increasing residual gas trapping (hysteretic effect) for each cycle. However, after a number of cycles this effect will reduce and injectivity will be comparable to the constant injection case with a low water saturation in the near well area.

7.2 Salt precipitation and back flow of brine phase

There have been reported incidents of reduced injectivity to the reservoir and one of the reasons that has been identified is the salt precipitation in the near well area. If the CO_2 being injected is free of water, it has been reported that the water in the near well area is evaporated. Hence, salt concentration in the remaining water increases with the potential end result of salt precipitating from the in-situ water. The precipitated salt prevents injectivity and increases the injection pressure with a risk of reaching the fracture pressure. Salt precipitation is governed by various parameters as composition of the water phase, residual water saturation, flow rate, pressure and temperature. Injecting CO_2 at high pressure and low temperature favours solubility of carbonate materials and may potentially increase injectivity. During the shut-in periods the temperature may increase and pressure decrease. This can lead to less carbonate solubility and more precipitation and injectivity problems at start up. Intermittent CO_2 injection can cause back flow of brine phase during shut-in periods and consequently affect salt accumulation in the near well area.

7.3 Ice and hydrate formation

The risk of hydrate formation depends on the water and gas compositions. Hydrates may also form when injecting CO_2 at low temperature and high pressures into a reservoir of lower pressure. After a shut in with increased temperature and reduced pressure a hydrate inhibition routine should be considered if hydrate formation is likely to occur. In extreme cases of pressure drop the Joule-Thomson cooling may cause freezing in the well and near well region in low pressure depleted gas fields. However, these highlighted issues must be carefully evaluated in each case as conditions will vary from project to project.

WP7 – RULES AND REGULATIONS FOR CO_2 SHIPPING

1 INTRODUCTION

This work package aims to provide an overview of the relevant laws, rules and regulations governing the building and operation of ships for international transport of CO_2, for the purpose of CCS.

CCS is a new field, and the amount of CO_2 that must be transported is expected to increase dramatically over the next years. The rules and regulations for the transport of liquified gases are not specific for CO_2, which has some different challenges than other gases. Therefore rules such as the IGC code are under revision, and new rules and guidelines are under development.

The scope of this report is to present an overview of the relevant rules and regulations regarding the international carriage of liquid CO_2, by ship.

The report is limited to the ships, with the battery limits placed at the ship flanges of the loading manifold, so rules and regulations for terminals are not included.

The overview does not include the general rules that are relevant for all ships.

This report is a summary of a literature search of the relevant rules and regulations pertaining to liquified CO_2 carriers.

2 INTERNATIONAL RULES AND REGULATIONS

2.1 International law

The transport of CO_2 between different countries is governed by international law and treaties. The relevant laws are:

- London Protocol; provisional application, ref. (124)
- Hazardous and Noxious Substances (HNS) Convention; not in force yet, ref. (125)
- EU Emissions Trading System (ETS), ref. (126)

2.2 ILO

The ILO (International Labour Organization) Constitution sets forth the principle that workers must be protected from sickness, disease and injury arising from their employment. Therefore, the ILO has standards for occupational safety and health, including exposure limits for chemical substances.

- ILO stipulates the occupational exposure limits for CO_2 as 5 000 ppm, averaged over an 8-hour workday, (TWA), and 30 000 ppm as Short-Term Exposure Limit (STEL), ref. (127)

2.3 IMO

IMO (the International Maritime Organization) is the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. The IMO is the main regulatory body for international shipping and may only be altered by a national state in its own waters. IMO publications

- IGC Code, International Code for The Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, as modified by Ch. 17.21 and 17.22. This code has been mandatory under SOLAS chapter VII since 1 July 1986. It applies to all ships regardless of their size, including those of less than 500 gross tonnage, engaged in the international carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C, ref. (128)
- MSC.1/Circ 1315 Guidelines for the approval of fixed dry chemical powder fire-extinguishing systems for the protection of ships carrying liquefied gases in bulk
- MSC.1/Circ 1461 Guidelines for verification of damage stability requirements for tankers
- MSC/Circ 406, Guidelines on interpretation of the IBC Code and the IGC Code and for the uniform application of the survival requirements of the IBC and IGC Codes.

2.4 ISO

Ref. (129)

ISO (International Organization for Standardization) is an independent, non-governmental international organization established to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges. ISO has established standards for different industries, including:

- ISO 28460:2010 Petroleum and natural gas industries – Installation and equipment for liquefied natural gas – Ship-to-shore interface and port operations.
- ISO 31010, Risk management - Risk assessment techniques
- ISO 17969 Petroleum, petrochemical and natural gas industries - Guidelines on competency for personnel

3 NATIONAL STATE RULES AND REGULATIONS

3.1 Flag State

A flag state is a country where a company registers its commercial and merchant ships. For ships engaging in international trade, once it is registered, the flag state has certain duties laid out in UNCLOS. In particular, under Article 94, the flag State must "effectively exercise its jurisdiction and control in administrative, technical and social matters over ships flying its flag" and take "such measures for ships flying its flag as are necessary to ensure safety at sea..."

SOLAS and the other International Conventions permit the flag administration to delegate the inspection and survey of ships to a Recognized Organization (RO).

3.2 Coastal/Shelf State

Coastal states, either individually, or as groups, may have additional rules and regulations that apply when sailing in their territorial waters.

An example of rules applied by a group of coastal states is the North Sea ECA.

An example of rules applied by an individual coastal state is the Norwegian rules for oil and gas installations, which apply if a vessel engaging in direct injection has control of the well. In this case, the vessel is regarded as an installation for the duration of the operation.

3.3 Inland Waterways

Several areas of the world have inland waterways, (rivers, canals, lakes etc) that are shared between different countries. Examples are the inland waterway system of Europe, the St. Lawrence Seaway and Great Lakes Waterway system, which is shared by the US and Canada, and the Mekong River Basin, in SE Asia, which flows through 6 countries. Travelling on these enclosed waterways is not regarded as "international voyages" and is not subject to IMO rules and regulations.

Therefore, there are specific rules and regulations governing the building and operation of vessels using these systems. These rules and regulations are organized in the same hierarchy as the international rules, with the top-level being rules by the relevant multinational grouping instead of IMO, and then certain classification societies have rules based on these.

3.3.1 Europe

European Rules and regulations:

There are several Europe-wide rules and regulations for the building and operation of vessels on the inland waterways:

- European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways (ADN). 2017, ref. (130)
- European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN). 2019, ref. (131)
- European Code for Inland Waterways. 2009, ref. (132)
- Safety Guide for Inland Navigation Tank-barges and Terminals, ref. (133)

3.3.2 North America

Great Lakes-St. Lawrence Seaway Rules and regulations:

Shipping vessels on the Great Lakes-St. Lawrence Seaway system belong to one of three categories: U.S.-flag operators, whose vessels are documented under U.S. law and primarily serve U.S. ports, Canadian-flag operators, whose vessels are documented under Canadian law and carry both domestic and bi-national commerce, and foreign-flag operators, whose vessels operate between Great Lake ports and overseas destinations.

Therefore, vessels trading on the Great Lakes-St. Lawrence Seaway, must be built in compliance with the flag state rules (Canada or USA).

Traveling on the seaway is governed by the "Seaway Handbook", ref. (134).

The Seaway Handbook contains the joint St. Lawrence Seaway Management Corporation's Seaway Practices and Procedures established under Section 99 of the Canada Marine Act and the Great Lakes St. Lawrence Seaway Development Corporation's Seaway Regulations established pursuant to the Saint Lawrence Seaway Act of May 13, 1954, as amended.

All vessels transiting the St. Lawrence Seaway, which exceed 300 gross registered tonnes must conform to the regulations and provisions found within the Seaway Handbook.

3.3.3 Southeast Asia

Mekong River Rules and regulations:

The Mekong River system runs through 6 states: Cambodia, Lao PDR, Myanmar, Thailand, Viet Nam,

and Yunnan Province, China. These countries have formed the Mekong River Commission (MRC), in order to standardize rules and regulations for shipping on the river, in order to facilitate trade. The work is ongoing, and will effect the building and operation of ships, and of terminals. One regulation in effect is:

- Mekong Vessel Inspection Scheme (MVIS), ref. (135).

4 CLASSIFICATION SOCIETIES

SOLAS and the other International Conventions permit the flag administration to delegate the inspection and survey of ships to a Recognised Organization (RO). This is in recognition of the fact that many flag administrations do not have adequate technical experience, manpower or global coverage to undertake all the necessary statutory inspections and surveys using its own staff. The degree to which a flag State may choose to delegate authority to a RO (Classification Society) is for each flag State to decide.

All the classification societies regulate ships for international trade, and some also regulate different inland waterways.

4.1 IACS

IACS was formed in 1968, as a result of the International Load Line Convention of 1930 and its recommendations. The Convention recommended collaboration between Classification Societies to secure "as much uniformity as possible in the application of the standards of strength upon which freeboard is based…".

Following the Convention, RINA hosted the first conference of major Societies in 1939 - also attended by ABS, BV, DNV, GL, LR and NK - which agreed on further cooperation between the Societies.

Relevant IACS rules and regulations are:

Ref. (136)

- Unified Requirements Gas Tankers (UR-G)
- Unified Interpretations Gas Carriers (UI-GC)

4.2 ABS

Ref. (137)

International:

- Rules for Building and Classing Marine Vessels – Part 5C, Specific Vessel Types Ch. 8
- Guide for Building and Classing Liquefied Gas Carriers with Independent Tanks 2021
- Requirements for the Class Notation Bow or Stern Loading and Unloading (BLU or SLU) for Oil Carriers, Liquefied Gas Carriers, or Chemical Carriers

Great Lakes-St. Lawrence Seaway:

- Steel Vessels for Service on Rivers and Intracoastal Waterways

4.3 BV

Ref. (138)

International:

- NR467 D R14 Part D – Service Notations, Chapter 9 Liquefied Gas Carriers

European:

- NR217 Rules for the Classification of Inland Navigation Vessels

4.4 ClassNK

Ref. (139)

International:

- Part N Ships Carrying Liquefied Gases in Bulk

Inland:

- Rules for the Survey and Construction of Inland Waterway Ships

4.5 DNV

Ref. (140)

International:

- RU-SHIP-Part 5 Ch. 7 Liquefied gas tankers

European:

- RU-INV Inland navigation vessels Pt.6 Ch.1. Sec.3 Liquefied Gases

4.6 LR

Ref. (141)

International:

- Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases in Bulk, July 2022

European:

- Rules and Regulations for the Classification of Inland Waterways Ships.

Great Lakes-St. Lawrence Seaway:

- Classification of Ships for Service on the Great Lakes and River St. Lawrence

4.7 RINA S.p.a

Ref. (142)

International:

- Rules for Classification of Ships (REP), Part E, Vol. 2, Ch. 9 Liquefied Gas Carriers 2023

5 INDUSTRY ASSOCIATIONS

Industry associations share information, discuss issues, develop standards and establish rules for best practice within their industry, at an international level. The goal is to establish relevant best practices to facilitate international compliance in order to allow international cooperation.

5.1 API

Ref. (143)

- API 520 Sizing, Selection, and Installation of Pressure-relieving Devices Part 1 & 2

5.2 IEC

Ref. (144)

- IEC 60092-502:1999, Electrical installations in ships - Part 502: Tankers - Special features
- IEC 60812:2006, Analysis techniques for system reliability – Procedure for failure mode and effects analysis (FMEA)
- IEC 60079-29-1, Explosive atmospheres – Gas detectors – Performance requirements of detectors for flammable gases
- IEC 15288:2008 Systems and software engineering – System life cycle processes

5.3 OCIMF

Ref. (145)

- Ship to Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases
- International Safety Guide for Oil Tankers and Terminals
- Mooring Equipment Guidelines

5.4 SIGTTO

Ref. (146)

- Liquefied Gas Handling Principles on Ships and in Terminals (LGHP4) Fourth Edition
- Application of Amendments to Gas Carrier Codes Concerning Type C Tank Loading Limits
- Liquefied Gas Fire Hazard Management - First Edition
- LPG Shipping - Suggested Competency Standards
- Liquefied Gas Carriers: Your Personal Safety Guide - 2nd Edition
- A Justification into the Use of Insulation Flanges (and Electrically Discontinuous Hoses) at the Ship/Shore and Ship/Ship Interface
- LNG Emergency Release Systems - Recommendations, Guidelines and Best Practices

- LNG Marine Loading Arms and Manifold Draining, Purging and Disconnection Procedure
- Recommendations for Liquefied Gas Carrier Manifolds
- Guidelines for the Alleviation of Excessive Surge Pressure on ESD for Liquefied Gas Transfer Systems
- Ship / Shore Interface for LPG/Chemical Gas Carriers and Terminals
- Recommendations for Management of Cargo Alarm Systems
- Recommendations for Relief Valves on Gas Carriers
- Recommendations for Designing Cargo Control Rooms
- Guidance on Gas Carrier and Terminal Gangway Interface
- ESD Systems
- Recommendations for Cargo Control Room HMI

6 FURTHER DEVELOPMENTS

The large-scale transport of LCO_2 presents some unique challenges for the ships, and the present rules are not CO_2 specific. Several rules and regulations are therefore under revision, or development.

6.1 IMO

A revision of the IGC Code, which will include more detail on CO_2 shipping, is expected to be finalized and published in 2026.

6.2 ISO

ISO is developing a technical report for the Transportation of CO_2 by Ship. At the present time, the status is “Under Development”.

6.3 SIGTTO

In June 2022, SIGTTO started work on the development of guidance to assist with safe operations involving the transport of carbon dioxide (CO_2) by ship.

6.4 Fiscal Flow Measurement

Currently, in Europe, the accuracy requirements for fiscal metering are dictated by the European Commission’s Measuring instruments directive (MID), ref. (147), and the International Organization of Legal Metrology’s Internal Recommendation on Dynamic measuring systems for liquids other than water (OIML R 117-1), ref. (148). With the expansion of CCS, international standards for fiscal metering will need to be developed.

ABBREVIATIONS AND DEFINITIONS

ABS	American Bureau of Shipping
AFS	Anti Fouling System
AiP	Approval in Principle
AP	Aft Perpendicular
API	American Petroleum institute
ARMS	Ammonia Release Mitigation System
BHP	Bottom Hole Pressure
BHT	Bottom Hole Temperature
BL	Baseline
BLS	Bow Loading System
BOG	Boil off Gas
BOR	Boil off Rate
BV	Bureau Veritas
CAPEX	Capital Expenditure
Cb	Block Coefficient
CCS	Carbon Capture and Storage
CCSO	Carbon Capture and Storage and Offloading Unit
CCU	Carbon Capture and Utilization
CI	Compression Ignition
CII	Carbon Intensity Indicator
CL	Centreline
ClassNK	Nippon Kaiji Kyokai
CO2LOS III	CO_2 Logistics by Ship Phase III
COLREGs	Convention on the International Regulations for Preventing Collisions at Sea
D	Depth
DC	Discipline Check
DCS	The Fuel Oil Consumption Data Collection System
DNV	Det Norske Veritas
DWT	Dead Weight Tonnes
ECA	Emission Control Area
ECL	External Cooling Loop

EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
E-fuels	Electro fuels
EGR	Enhanced Gas recovery
EOR	Enhanced Oil Recovery
ESD	Emergency Shut Down
ETS	EU Emissions Trading System
EU ETS	EU Emission Trading System
FAME	Fatty Acid Methyl Aster
FMEA	Failure Mode and Effects Analysis
Fn	Froude number ($Fn = v/\sqrt{(g*L)}$)
FPSO	Floating Production Storage and Offloading
FSI	Floating Storage and Injection Unit
FSRU	Floating Storage and Re-gasification Unit
GHG	Greenhouse gases
GM	Distance from centre of gravity to metacentre.
GT	Gross Tonnage
GWP	Global Warming Potential
HCCI	Hydrogen Promoted Homogeneous Charge Compression Ignition
HDO	Heavy Diesel Oil
HDRD	Hydrogenation -derived renewable diesel
HEU	Highly Enriched Uranium
HFC	Hydrofluorocarbon
HFO	Heavy Fuel Oil
HNS	Hazardous and Noxious Substances Convention
Hs	Significant wave height
HSE	Health, Safety, and Environment
HVDC	High Voltage Direct Current
HVO	Hydrotreated Vegetable Oil
IACS	International Association of Classification Societies
IAEA	International Atomic Energy Agency
IC	Internal Combustion

ICL	Internal Cooling loop
IDC	Inter Discipline Check
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in bulk
ILO	International Labour Organization
IMO	International Maritime Organization
IS Code 2008	The International Code on Intact Stability, 2008
ISO	International Organization for Standardization
kts	Knots: nautical miles per hour
LCA	Life Cycle Analysis
LCB	Longitudinal Centre of Buoyancy
LCG	Longitudinal Centre of Gravity
LCO_2	Liquid Carbon Dioxide
LEU	Low Enriched Uranium
LNG	Liquefied Natural Gases
LP	Low Pressure
LPG	Liquified Petroleum Gas
Lpp	Length between perpendiculars
LQ	Living Quarter
LR	Lloyd’s Register
MARPOL	International Convention for the Prevention of Pollution from Ships
MARVS	Maximum Allowable Relief Valve Setting
MAWP	Maximum Allowable Working Pressure
MDO	Marine Diesel Oil
MEA	Monoethanolamine
MEG	Monoethylene Glycol
MEL	Master Equipment List
MHI	Mitsubishi Heavy Industries
MID	Measuring Instruments Directive
MLC 2006	Maritime Labour Convention, 2006 - ILO
MRC	Mekong River Commission

MSC	Maritime Safety Committee
MVIS	Mekong Vessel Inspection Scheme
NEF	Nordic Electro Fuel
nm	Nautical mile
NZE	Net Zero Emissions
OCIMF	The Oil Companies International Marine Forum
OGCI	Oil and Gas Climate Initiative
OIML	Organisation Internationale de Metrologie Legale
OPEX	Operating Expenditure
PEMFC	Photon Exchange Membrane Fuel Cells
PS	Photosensitizer
PSV	Pressure Safety Valve
RINA S.p.a	Registro Italiano Navale
RO	Recognized Organization
ROS	Reactive Oxygen Species
RPM	Revolutions per minute
SAL	Single Anchor Loading
SEEMP	Ship Energy Efficiency Management Plan
SFI	Skips Forsknings Instituttet, numbering system
SI	International System of Units
SIGTTO	Society of International Gas Tanker and Terminal Operators
SMR	Small Modular Reactors
SOE	Sinopacific Offshore & Engineering CO. LTD.
SOFC	Solid Oxide Fuel Cells
SSAS	Ship Security Alarm System
STEL	Short Term Exposure Limit
STL	Submerged Turret Loading
T	Draught
THP	Top Hole Pressure
THT	Top Hole Temperature
TLU	Tower Loading Unit
Tr	Roll period
TRL	Technology Readiness Level

TWA	Time-Weighted Average
UNCLOS	United Nations Convention on the Law of the Sea
UR	Unified Requirement
VCO_2	Vapour Carbon Dioxide (CO_2)
W2W	Walk to Work
WAG	Water Alternating Gas
WP	Work Package
WRI	World Resources Institute

Block Coefficient	The ratio of the underwater volume of the ship's hull to the volume of a rectangular block of the same length, width, and height.
Boil off Gas	This is gas that evaporates as a result of heat ingress into the storage tanks
Boil off Rate	This number is often given as BOG in % of stored volume during 24 hr
Dead Weight Tonnes	The vessel's weight carrying capacity, not including the empty weight of the ship.
Dense phase	CO_2 above the critical pressure but not necessarily above the critical temperature. In this area there is no real phase change as there is no change of enthalpy associated with the transition from ”liquid” to ”gas”. It also covers the CO_2 arriving from a long distance pipeline where the pressure is above the critical pressure to avoid phase change in the pipeline.
Depth	Of hull; the vertical distance measured from the top of the keel to the underside of the upper deck at side.
Energy Efficiency Existing Ship Index	An index that estimates grams of CO_2 per transport work (g of CO_2 per DWT-mile), for existing ships.
Joule Thomson effect	This is the change in temperature happening as a result of isenthalpic expansion through a nozzle or an orifice. A positive J-T coefficient corresponds to cooling, and this is the case for both the CO_2 and the ammonia.
Length between perpendiculars	Length of the summer load waterline from the stern post to the point where it crosses the stem
Liquid Carbon Dioxide	CO_2 in liquid phase at subcritical pressure
Partly open refrigeration circuit	A partly open refrigeration circuit is when the last step in the cooling is a pressure reduction and a separator where the cooling is due to the Joule Thomson effect.
Q orifice	Standard orifice sizes A to T are defined by API. The letters refers to a specific orifice area

Significant wave height	The average wave height, from trough to crest, of the highest one-third of the waves.
Vapour Carbon Dioxide (CO_2)	Gaseous CO_2 at subcritical pressure.

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