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LNG-ZERO

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Deliverable D4.1 Identified knowledge gaps for CO_2 storage and transfer

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Document History

This document has been through the following revisions:

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Version 1.1	05/04/2023	Peter van Os	Second draft after review of the partners
Version 1.2	04/07/2023	Peter van Os	Third draft with comments of CC
Version 2.0	25/07/2023	Peter van Os	Final version (no further comments received)

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1 INTRODUCTION

This report summarizes the activities performed within Task 4.1 of the LNG-ZERO project.

Participants in this task are: TNO, Anthony Veder, Heerema Marine Contractors Nederland SE, Conoship International, Carbon Collectors, Lloyd's Register, Shell and VDL AEC Maritime BV.

Task 4.1 is all about the identification of knowledge gaps for CO_2 onboard storage and transfer. The objective of this task is to determine the knowledge-gaps concerning the most relevant parameters in the various storage and transfer processes, and their possible expected impact over the process-chain on safety, ecology and economy of the processes and related technologies (existing and to be developed).

The task consists of the following subtasks:

ST4.1.1 Onboard storage: CO_2-tank-containers or fixed CO2-tanks

Research is performed by CONO, supported by LR and HMC, on the extra hazards and requirements related to a possible application of CO_2-tankcontainers (compatible with road transport) for storage of captured CO_2 on ships (in a maritime environment, for longer duration, in heavy seaways, near LNG installations). A brief overview of relevant relations of various CO_2 storage temperatures and pressures to tank-storage technologies and hazards will be determined, to prioritize further investigations in Task 4.2 - Onboard storage.

ST4.1.2 Transfer from ship to shore location

AV, CONO and Shell will investigate which technical- and risk-parameters are important for unloading of CO_2 tank-containers to a general quay and directly to a truck. The same aspects will be investigated (in cooperation with WP5) for the developing CO_2-receiving port locations of Porthos in Rotterdam and Northern Lights in Norway, considering expected temperatures, flow rates, pressures and transferring systems. Resulting knowledge will be input for Task 4.3 - Transfer of CO2 from ships to shore.

ST4.1.3 Ship-to-ship transfer of LNG and CO2

For semi-stationary offshore work-ships (f.e. pipelaying- and cable-laying vessels, windfarm-construction vessels and crane-vessels) fuelled by LNG it is important that they can stay offshore at their work-position. Offshore bunkering of LNG and transfer of CO_2 out in the open ocean has not yet been realized. For ship-to-ship transfer, the main technical- and risk-parameters that are important for CO_2 unloading operations in calm waters in ports and for various sea-states will be investigated by HMC, LR, CONO, CC, VDL and AV. The offshore operations are important for semi-stationary offshore work ships (f.e. pipelaying- and cable-laying vessels, wind-farm construction vessels and crane-vessels such as the Sleipnir) that work and stay offshore for very long periods. Various types of ships, transfer technologies and sea-conditions will be considered to determine most relevant risk-related issues to be investigated in Task 4.4 - Ship-to-ship transfer of LNG and CO2.

ST4.1.4 Offshore transfer of CO2 from ship to CO2-Geo-storage units

To finally store the CO_2 in empty offshore gas fields, offshore gas-production-platforms will be refitted with CO2-receiving facilities and technology for injecting the CO_2. The transfer of the captured CO_2 from a CO_2 transporting barge or ship to an offshore CO2-receiving facility will be investigated by CC and CONO to determine the most relevant technologies and risk-parameters as input for Task 4.5 - Offshore transfer of CO2 from ship to geo-storage-unit.

The approach for each task is to:

1 Determine the state-of-the art.
2 What is needed for LNG-ZERO.
3 If there is a gap between 1 and 2, describe this gap and if possible, what needs to be done to close that gap.

2 Onboard storage: CO_2-tank-containers or fixed CO_2-tanks

The scope of this research is limited to the onboard storage of CO_2 in its liquid state, which is in terms of both volume and weight is the most efficient way to store CO_2. Other ways of onboard storage are possible, such as chemically or physically binding the CO_2 to another substance, but these are not within the scope of this project.
The knowledge gained in this work package will be integrated into a *knowledge model on onboard captured CO_2 storage*, for future reference.

2.1 Technology and hazards

Much is known about the general risk associated with the storage of CO_2, which is done in many industries. Additional investigations regarding the storage of liquid CO_2 onboard ships are ongoing in other projects, such as EverLoNG. The identification of knowledge gaps regarding technology and hazards is in this project mostly focused on the additional hazards related to storage of CO_2 in tank containers (or portable tanks) opposed to storage in fixed tanks.

2.1.1 Current knowledge

Storage technology for liquid CO_2 is mature. In several industries, CO_2 is used as feedstock and liquid CO_2 is stored on-site. Transport of CO_2 by truck, train or ship is widely practiced. Intermodal CO_2 tank containers are available from many manufacturers.
Regarding any additional hazards regarding onboard storage of captured CO_2, investigations are ongoing in other projects, such as EverLoNG.
Technologies and hazards concerning intermodal tank containers used for transport of CO_2 are largely known and dealt with by means of regulations (see the next section).
Relations between storage temperatures and pressures. Qualitatively, the effects of these different temperatures and pressures on the cost of a storage tank are also known. A brief overview of this is given below, along with the most important relations with regard the required energy for liquefaction of the captured CO_2.

Storage pressure (bara)	**bara**	**8**	**17**	**40**
Temperature	°C	-46	-25	5
CO2 density	kg/m3	1140	1020	885
Required cooling energy	-	High	Intermediate	Low
Required compression energy	-	Low	Intermediate	High
Required amount of insulation	-	High	Intermediate	Low
Pressure tank weight	-	Low	Intermediate	High

Generally, two types of insulation are applied for Liquefied CO_2 (LCO2) storage tanks:

- Single walled pressure vessel with PUR insulation (generally with metal or plastic protective cladding)
- Double walled tank with perlite and vacuum insulation

A perlite with vacuum insulated tank has better insulation performance than a PUR-insulated tank.
Depending on several parameters (like the LCO2 delivery process, pressure and temperature, required holding time, etc.), PUR insulation is expected to be acceptable for large-volume tanks instead of vacuum insulation because cost and empty weight of PUR-insulated tanks is expected to be lower, and the impact of the insulation performance decreases with tank size. Moreover, the construction of double walled tanks poses more of a challenge for large, heavy tanks than for small tanks.

2.1.2 Knowledge gaps

The optimal storage tank for the captured CO_2 will be different for each case. To be able to assess the right choice of storage tank in an early design stage, more detailed knowledge is required of the consequences of the different tank design choices on the cost of the storage tanks and related systems. For instance, an analysis is to be done on the type of insulation related to tank dimensions, pressures, and environmental conditions, and what the consequences of these factors are for the cost of the tank. Based on this knowledge, an assessment can be done of the most favourable storage conditions.

The focus in this task is on determining the cost of the tanks themselves, as well as relevant aspects of the tank for the ship design (such as weight), in a generalized way (so independent of specific case studies). The final choice of storage tank for a specific case will depend on more factors (such as client priorities and the CO_2 logistics and infrastructure investigated in WP5) and is in this project part of WP2 (ship integration).

An overview of the most important factors determining the cost of a CO_2 storage tank is given below. The relations between these factors are to be identified and, where relevant and possible, quantified. For every factor, it will be evaluated in this project whether this factor is case specific, or a choice can be made to establish a value for this factor and define it as a standard.

Cost determining factor	**Comments**
Tank type	Fixed, or interchangeable: portable tank T50 (single walled) or T75 (double walled), or custom portable tank
Tank capacity	Range: 20 m^3 to 800 m^3
Design pressure	Range investigated: - 0.5 barg to abt. 40 bar.
Design temperature	Range: -78°C to +50°C
Type of insulation	PUR + cladding or vacuum + perlite
Required holding time	This factor will determine the required insulation performance of the tank.
CO_2 composition	Impurities in the CO_2 (e.g. water) could influence, for instance, the required tank material
Class regulations	All main Class societies have their own rules and their own interpretation of statutory rules. Experience has shown that this interpretation can be different between different offices of the same class society, and even between different surveyors at the same office.
Design codes	See next section
Tank orientation	Vertical or horizontal, longitudinal or transverse
Tank location on ship	Inside or outside (exposure to waves & weather), Also relevant for determining dynamic loads.
Tank material	Relevant factors: design temperature, CO_2 composition, client wishes, weight limitations. Pressure vessel materials: P355NL1, P460, P690, 9%Ni-steel, Stainless 304, Stainless 316 Outer tank materials (for double walled tanks): Carbon steel, Stainless 304, Stainless 316. With coating.

The process of filling and emptying the CO_2 tanks is to be defined, as is the way in which the pressure in the storage system is controlled. This is very relevant for, for instance, the design pressure of the tank. This definition is to be done together with the other work packages, since it is relevant for the ship's systems WP2, the capture- and liquefaction systems (WP3), the logistic systems (WP5) and procedures and safety and performance standards (WP6 and WP7).
Other knowledge gaps identified within the scope of this project are mostly concerning the specific case of intermodal tank containers that, while the ship is sailing, are connected to the capture system and being filled with CO_2 and need to be taken off the ship and replaced when full.

- For the loading (during operation of the capture system) and unloading of the containers with CO_2, requirements to the connections and verification of their working and gas-tightness should be defined. The tank connections should be easy to connect and disconnect, while being suitable for prolonged unattended operation while connected. Moreover, for easily interchanging of containers, either the type and location of the connection should be identical for all tanks, or flexible connections are to be used. This must be defined.
- For the structural fixation of the tank on the ship, it should be determined whether standard ISO couplings such as twistlocks are suitable or additional lashing is required, considering the clearances of the twistlocks in relation to the flexibility of the process connections (CO_2 lines).
- With regular coupling and decoupling of the connections, there is a risk of moisture entering the system, causing ice crystals in the system which could damage the components of the system. Similarly, dirt or other contaminants could enter the system. Additionally, the frequent swapping could cause more wear and tear on the connections, resulting in a higher risk of faulty connections. Related to the previous point, it should be specified whether purging is required for all parts that are exposed to the atmosphere every time a tank is replaced (if so, facilities for this are required onboard)
- An assessment should be made whether to use UN portable tank type T75 or T50 as a standard. In principle, both tank types could be used, depending on several factors such as operational pressures and temperature, filling speed of tank, design pressure, holding time, etc.
- The logisitics (transport, storage onshore, handling, etc) of the CO2 storage containers needs to be looked at / defined.

2.2 Regulations

2.2.1 Current knowledge

Below is an overview of the most important regulations that are or might be applicable to LCO_2 tanks installed on ships and tank containers that are used for onboard carbon capture.
Since the tank containers are to be suitable for transport by both ship and road, and perhaps other modes of transport, it is logical to refer to existing regulations regarding the transport of CO_2 in standard tank containers instead of coming up with a unique design for a tank container for SBCC systems. This leads us to two options for the standard tank container to focus on in this project: UN portable tank types T50 and T75.
In this overview, the focus is on regulations that are specific for this intended use, where the tank container is used onboard as part of the ship systems, and once taken off the ship it should be regarded as (intermodal) tank container.
Additional to the regulations listed below, other regulations might also be applicable, but these are typically more general regulations for either intermodal containers or pressure vessels. These regulations are to be complied with but are not expected to pose any challenges specific to the intended use of these tank containers.

European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR)
ADR regulations govern the transport by road of dangerous goods, including CO_2. If the tank is to be transported by road (which will generally be the case for tank containers), ADR is to be complied with. ADR is applicable in Europe and several countries outside Europe. In case of transport by train, the relevant regulation is the RID (Regulations Concerning the International Transport of Dangerous Goods by Rail).

International Maritime Dangerous Goods (IMDG) Code
The IMDG Code governs the transport by ship of dangerous goods in packaged form, which includes CO_2 in tank containers. However, this code deals with containers that are onboard a ship as cargo and as such are closed and not connected to any other systems. The tanks are not to be filled or discharged onboard. The applicability of these regulations for onboard carbon capture thus seems limited. However, it is conceivable that during a trip, a full tank container is disconnected from the capture system (e.g. when the connection is swapped to an empty tank container). In that case, the IMDG Code could be applicable again.

International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)
Ships carrying liquefied gases in bulk must comply with the IGC Code. The Code is primarily meant to deal with ships carrying gas as a cargo. Hence the abbreviation IGC Code, which stands for International Gas Carrier Code. It could be debated whether a ship capturing and temporarily storing it's own CO_2 emissions can be considered a gas carrier, but on large vessels the amounts of captured CO_2 to be stored onboard can well exceed the cargo capacity of a small CO_2 carrier. Moreover, the risks associated with CO_2 tanks used in an onboard carbon capture system are similar to those associated with a CO_2 cargo tank. Hence, it seems likely that most of the regulations in the IGC code are applicable to ships with an onboard carbon capture and storage system. In consultation with class societies during this project, class societies generally refer to the IGC Code as the applicable regulations for CO_2 storage tanks in SBCC systems.

International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)
The IGF Code governs ships that use gas, such as natural gas, or flammable liquids, such as methanol, as fuel. Although CO_2 is neither a fuel nor flammable, the onboard carbon capture and storage system could in some respects be seen as a fuel supply system, and some of the requirements in the IGF Code could still be relevant. However, consultation with several class societies during this project has shown that the IGF Code is considered <u>not</u> applicable for CO_2 storage tanks in an SBCC system.

Class regulations
In addition to the international regulations mentioned above, class societies have their own rules with regard to, for instance, the materials to use for the tanks. Hence, the requirements for the CO_2 tanks could differ between different class societies and thus the requirements for a specific ship will depend on its class

society. There is no known overview of exact differences between the class societies in this respect, and experience teaches that even within one class society, requirements differ between projects.
No class requirements are in place yet that are specific for onboard carbon capture, although several class societies are working on this[1,2,3].

2.2.2 Knowledge gaps

Several relevant regulations exist for onboard CO_2 tanks, whether fixed or portable. The main knowledge gap to be closed here is to determine which regulations should be applied in which situation. This is not fundamental knowledge but depends on interpretation by regulatory bodies and class societies. Several class societies are already working on the development of regulations for onboard carbon capture and storage systems. Hence, logically, closing of this knowledge gap will be done by means of discussion with class societies and analysis of their (future) publications. As participant in LNG-ZERO, Lloyd's Register will be important in the discussions, but to gain an impression of all opinions in the industry, other class societies should also be consulted.
For tank containers, it is likely that the applicable regulations are dependent on the actual situation of the tank at a specific moment: when the tank container is on the ship, connected to the capture system, the applicable regulation might be the IGC code. When the container is taken off the ship to be transported, however, ADR is the applicable regulation. If these different regulations are not consistent with each other (e.g., the pressure safety settings differ between regulations, or the required type of fixation to the ship: are foundations required, or is fixation by means of twistlocks with or without lashing sufficient?), this could cause conflicts for the tank design. These conflicts are to be identified. Subcontractor Cryovat has experience with this related to the development of an intermodal tank container for LNG, suitable to be used as interchangeable fuel tank onboard ships.
Based on the results of the discussions, it can be determined whether existing regulations sufficiently cover the onboard storage of captured CO_2 or additional regulations are needed.

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[1] As of December 2022, ABS has released it's "Requirements for onboard carbon capture and storage".
[2] Lloyd's Register expects to include requirements for carbon capture systems into it's Rules per July 2023.
[3] As of January 2023, BV has included the additional service feature **OCC** for ships fitted with a CCS system to its rules (NR467)

3 Transfer from ship to shore location

3.1 Learnings from Coral Carbonic

3.1.1 Properties and hazards of Carbon Dioxide

When transferring liquid carbon dioxide, caution should be practiced with regards to the temperature and pressure. Carbon dioxide cannot exist as a liquid below the triple point pressure of 5.18 bara = 4.18 barg. The triple point temperature, where all three phases can co-exist in equilibrium, is -56.6 °C. Carbon dioxide at a temperature above the critical temperature of 31.1°C cannot form a liquid by an increase in pressure alone. The critical point pressure is 73.8 bara. Depressurized liquid will transfer to dry- ice.
Gaseous carbon dioxide is non-flammable, but odourless and colourless and it is heavier than air. Therefore, it spreads at grounds level causing oxygen deficiency and could cause suffocation. Flow agitation can cause build-up of electrostatic charge due to liquids low conductivity. At high temperatures will react violently with ammonia.
Liquefied cryogenic gases expand as much as 830 times when allowed to vaporize. One kg of solid CO_2

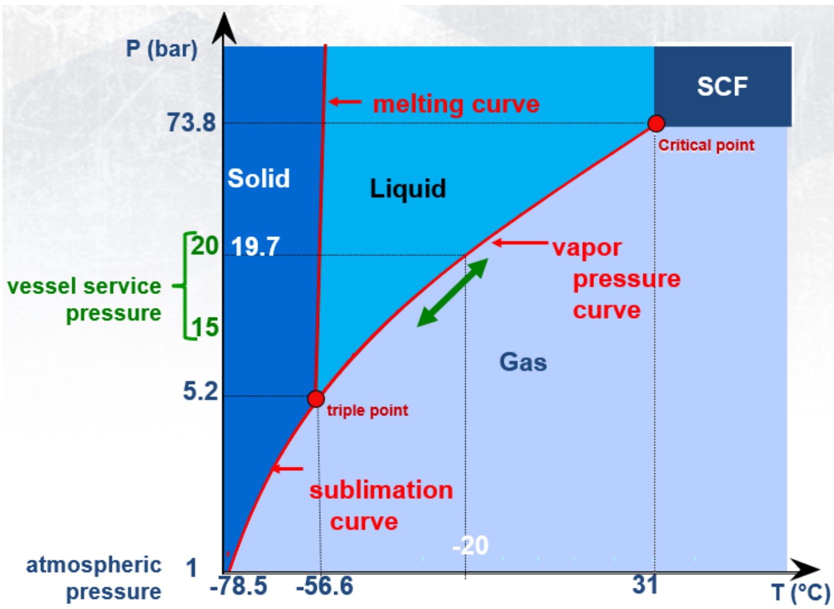
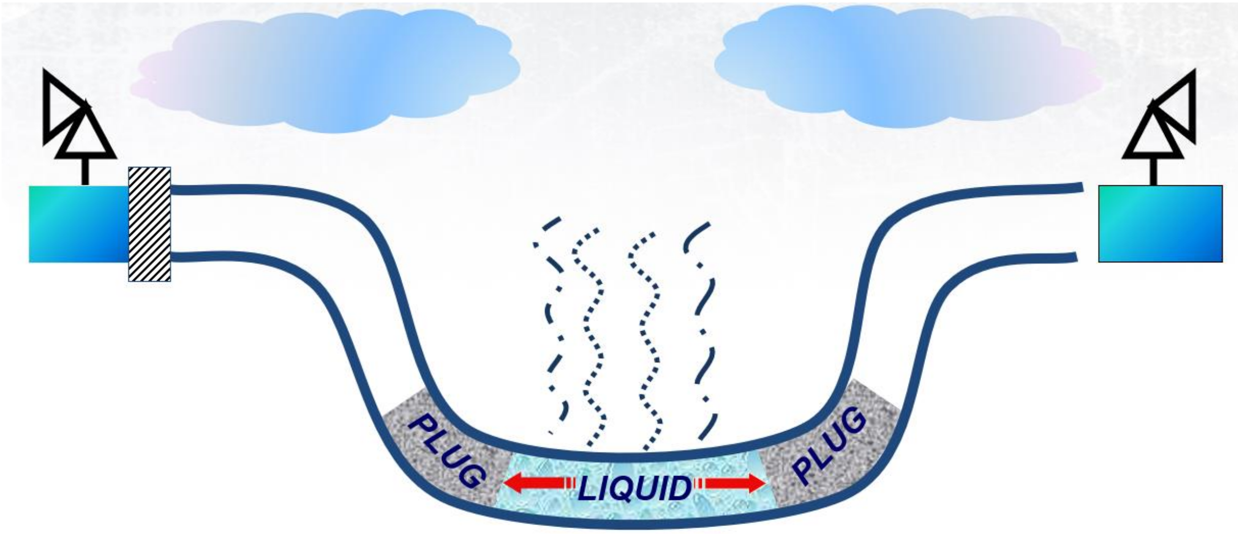


Figure 1 Aggregate states in pressure - temperature diagram

emits 540 liters of gas at 15°C / 1 bar. Dry ice plugs can form inside hoses and piping when liquid carbon dioxide pressure decreases below its triple point. Dry ice can be compacted into a plug which can trap gas. The pressure behind or within the plug may be ejected from the impact of the dry ice plug and/or the sudden movement of the hose or pipe as the plug ejects. This can occur in a liquid flexible hose, e.g. in humid weather conditions, in case of simultaneous purging of the customer vessel. CO2 can accumulate in plug piping or at the end of purges. If there is no pressure upstream it is sufficient to allow the dry ice plug to sublimate without doing any disassembling. A rigid portion of the flexible hose may indicate that there are dry ice plugs. If there are multiple, the space between them is under increasing pressure due to trapped liquid CO_2, which will warm up. In this situation, the flexible must be allowed to warm up by itself until the portion is no longer rigid. If the flexible has been disconnected to accelerate warming, the operator must not stand in front of any tank or tanker outlet.



Dry ice plug formation may occur in any pipe of the tank or tanker, or inside the transfer pump in the tanker. Dry ice plugs, which typically start on the smaller diameter pipes, can give the technician the wrong information regarding levels and pressure. They may be localized due to a small leak in a valve or flange, or a relief device that did not close properly. Another important hazard is hose whips. A safety cable should always be used, especially when disconnecting the hose.

3.1.2 Cargo operations

The operating crew on deck must wear proper PPE, including: coverall, safety helmet, safety goggles, safety shoes, hand gloves, portable Vhf radio for communication, portable gas detector. The steps during loading and unloading are as follows:

1. Connect the hoses, ensuring sagging is prevented as much as possible in order to prevent liquid CO2 pockets forming.
2. Purge the hoses minimum three times with gaseous CO2.
3. Pressurize the hoses.
4. Connect ship-shore cable system.
5. Open ship-shore manifold
6. Advise to start shore pump (loading) / ship's pump (unloading)
7. Monitor the tank level
8. Stop loading/unloading
9. Shut off ship-shore manifold
10. Disconnect ship-shore system cable
11. Depressurize vapour return hose.

Depressurizing the lines should be carefully done using the following steps. Open the "gas to liquid line" valve on the ship and the vent valve on the liquid line on the jetty. Blow the liquid CO2 out until the purge exhaust is only gas for one minute. Keep monitoring the pressure in the line during the liquid freeing procedure, it should not be allowed to drop under 10 barg. After all liquid is removed, close the vent valve on the jetty and pressurize the line to tank. Check if the pipe at the ship-manifold is free of liquid by opening the vent valve on the ship for 5 seconds. If it is suspected there is still liquid in the line, continue the liquid freeing process. When it is expected that the pipe and hose are free of liquid, continue with depressurization of the hose via the vent on the jetty. If the pressure doesn't drop uniformly on the ships' manifold pressure indicator to below 4 barg this indicates that there is still liquid in the line or hose and dry ice is forming. If the pressure does not drop down to zero, it is suspected that there is a dry ice plug in the line or hose. Ensure that both vent valves, ship's manifold side and shore side, are closed. Contact loading master for assistance. Pressurize the line with gas from both the jetty and the ship and let the line warm up. The dry ice will sublimate after which it is safe to start over from the beginning with the liquid freeing. After finishing the liquid freeing, close all valves and open the drain valve before disconnecting the hose. When disconnecting the hose, make sure to loosen first the lower bolt just in case there is remaining pressure, so it blows down and not up and into the operator. Make sure there is no dry ice remaining inside the line and do not stand in front of the manifold while installing the blind flange.

3.2 Bridging towards LNG-zero

The previous chapter describes the protocol that Anthony Veder used when operating their liquid CO2 carrier. This can in principle be copied to ship-to-shore transfer of liquid CO2 in the LNG-zero project, but for later application more details about the terminal, the ship’s size etc. should be known. Then, to bring the knowledge of CO2 ship-to-shore transfer up to the desired level a compatibility study needs to be done based on the technical details of the receiving terminal and the ship. The main issue with liquid CO2 is the hazard of dry ice forming at lower pressures. This should be kept in mind for example when deciding on the transfer piping length.

4 Ship-to-ship transfer of LNG and CO2

4.1 Ship-to-Ship transfer of LNG

LNG is natural gas that has been changed into a liquid state by cooling it to -162°C (-260°F), at 1 barg pressure, through a refrigeration process at liquefaction plants. It is a cryogenic liquid that is odorless by nature, and is clear, non-corrosive and non-toxic. It is composed principally by methane, together with ethane, propane and other heavier hydrocarbons. When LNG is warmed up, it re-gasifies. Some of its key characteristics are:

- Comprises mainly methane, colorless, cryogenic liquid
- Atmospheric boiling point of -163º C to -160º C
- Auto-ignition temperature of 595º C
- Density of 458-463 kg/m³ (depending on composition)
- LNG takes up about 1/600th of the volume of natural gas
- Evaporated natural gas at temperatures lower than -110° Celsius is heavier than air, and will thus spread by gravity. At higher temperatures, natural gas is lighter than air and will thus disperse.

4.1.1 State-of-the Art LNG Bunkering System

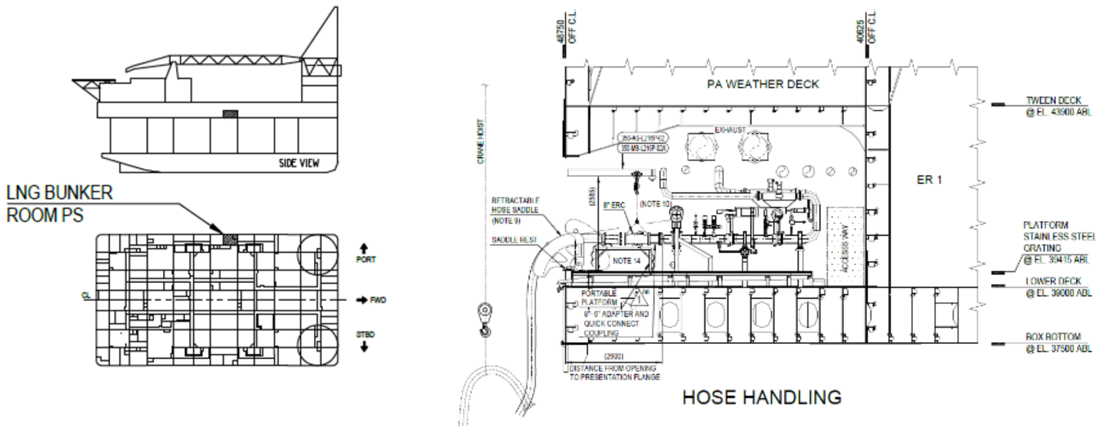
The LNG system onboard the Sleipnir consists of 8 vertical type C, LNG storage tanks located in the columns 2 and 3 of the Sleipnir with an individual total net volume of 1151 m³, but a max filling volume of 1001 m³ at a temperature of -162° Celsius as per IGF code (International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels). Each of the storage tanks holds 2 internal submerged pumps (LNG service pump) to supply LNG towards processing facilities that supply Natural Gas (NG) to the Dual Fuel Generators (DFG).

On top of each LNG storage tank, a liquid and gastight Tank Connection Space (TCS) is located which holds the interfaces between storage and processing facilities for each of the 4 engine rooms.

4.1.2 What is needed for LNG-Zero

LNG Bunker Station

For bunkering LNG, a bunker station is provided on each side of the Sleipnir (port side and starboard side midship area on the weather decks). Each station is equipped with 2 LNG connections (8”), 2 vapor connections (6”), data connection reels (for the Universal Safety Link), a flowmeter, a nitrogen purge connection as well as a chromatograph for quality measurement of the LNG. A control station with a view on the connection manifold is provided also, but in a safe area at each bunker station for control of the bunker-sequence. Inside the control station, an operator station with viewer functionality is installed to monitor the bunker-related processes of the LNG plant. The bunker station is segregated from adjacent weather deck areas by means of lockable doors -which are to remain closed during bunkering, thus ensuring that solely the bunker station is classified as hazardous area Class 1 during bunkering. The bunker station is outfitted with dedicated ventilation for air extraction. For hose handling during the connection of the bunker hoses/lines, pneumatic pull-in winches are provided for at the bunker stations. Furthermore, both the 10.000 mT Tub Mounted Cranes on board the Sleipnir have enough capacity and outreach to perform or assist in the hose handling when required. The LNG system design allows for bunkering from one side of the vessel only.



Bunker Vessel Mooring system

For mooring of bunker barges or bunker vessel alternatively, a Barge Mooring System is provided for on Sleipnir. The systems consist of 12 single-drum and 2 double-drum mooring winches. The forward system is installed on the Tween Deck and consists of 6 single-drum barge mooring winches, the port and starboard system each consist of 3 single-drum barge mooring winches on Lower Deck and 1 double-drum barge mooring winch on the aft Main Deck. The barge mooring winches are rated for 30 mT x 0~12.5 m/min duty pull on the 1st layer. The caliper brake capacity is rated at 55 mT and the parking (band) brake holding force is 100 mT on the 1st layer. Besides the winches, a total of 12 capstans are provided for. Each capstan is rated for a pulling force of 30 mT x 0~12.5 m/min and a Safe Working Load of 50 mT. The forward system consists of 4 capstans on Main Deck (fwd), the port and starboard system each consist of 3 capstans on Lower Deck and 1 capstan on Main Deck (aft).
The synthetic mooring ropes used on the sscv Sleipnir (96 mm x 220 m, MBL 150 mT) are provided with a weak link to ensure that rope assembly Minimum Breaking Load (MBL) is in line with Working Load Limit (WLL) of the barge mooring equipment.
To provide for an elastic buffer along the side shell during mooring of a barge or vessel, sscv Sleipnir is equipped with Yokohama floating pneumatic fenders (D x L = 4500 x 9000).

Reference is made to HMC's LNG Bunker Management Plan M335-X-100-PC-0008 rev 0 (March 2019).

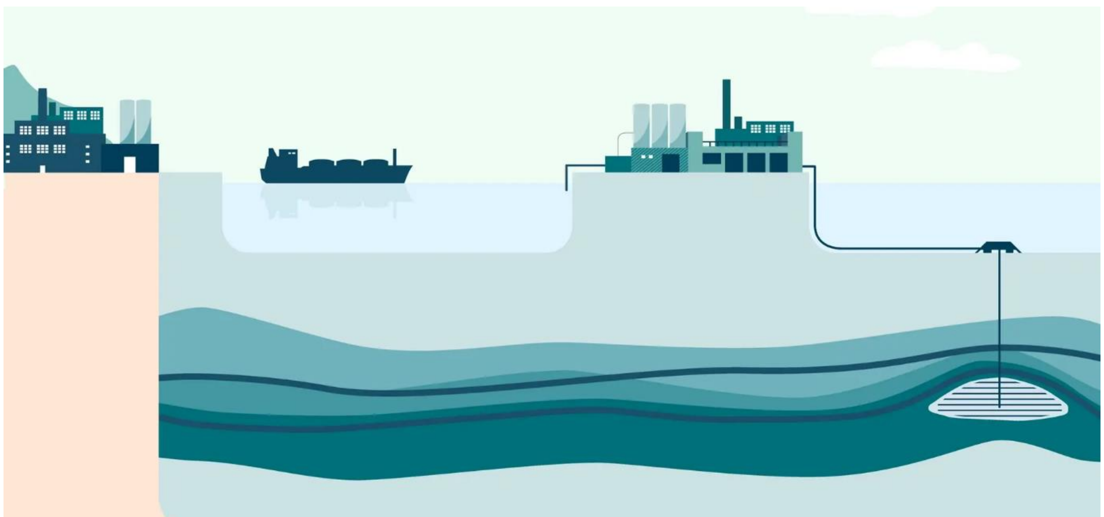
4.1.3 Knowledge Gap

For bunkering LNG there is sufficient practical experience gained during several bunkering operations. These bunkering events however all took place at nearshore locations (Norway, AmoyFjord and Gibraltar or at Rotterdam quayside).
No offshore bunkering has been taken place so far. It is worth investigating the mooring of a bunker vessel alongside the Sleipnir offshore to determine the operational boundaries of such an operation.

4.2 Ship-to-Ship transfer of CO_2 offloading System

4.2.1 State-of-the Art CO2 Offloading System

Offshore transfer of CO_2 from a ship like the Sleipnir to a bunker vessel has not been done before. The state-of-the-art for this specific purpose is therefore non-existent. However, CO2 transfer from an onshore location to a CO2 carrier is already done for smaller scale food-grade CO2 by companies such as Larvik shipping and for larger volumes it is being developed by several parties, such as the joint cooperation between Equinor, Shell and Total called Northern Lights, and Carbon Collectors. The Northern Lights project encompasses the capture of CO2 from cement production and a waste-to-energy plant in the Oslofjord region and the shipping of liquid CO2 from these sites to an onshore terminal on the Norwegian west coast. From there, the liquefied CO2 will be transported by pipeline to a subsea storage location in the North Sea for permanent storage. Operations are scheduled to start in 2024. Carbon Collectors plans to collect CO2 from various sources to deliver and inject it directly into various offshore storage locations.



Northern Lights JV and Kawasaki Kisen Kaisha, Ltd. (“K” LINE) have signed contracts for “K” LINE to operate the two first 7,500 m3 liquefied CO2 ships. The ships will be delivered in 2024 and will contribute to the world’s first full-scale carbon capture and storage (CCS) value chain.

Technip Energies has been selected to design and supply the CO2 loading systems onboard the Northern Lights vessels.

Technip Energies offers a combination of expertise and experience in offshore transfer systems. They deliver a full range of solutions for LNG, FSRU and recently also CO_2 applications. They analyze the specifications and conditions of each project before recommending the most suitable transfer system available from their solutions portfolio.

4.2.2 What is needed for LNG-Zero

On the 20th of February 2023, HMC had a meeting with representatives of Technip Energies to discuss a possible CO_2 offloading system for the Sleipnir. Technip Energies has emphasized they are interested in the supply of such a system. They have the inhouse capabilities and expertise to design such a system and deliver according the specifications determined by HMC/LNG-Zero partners. It will be a purpose build system tailormade for the Sleipnir.
Benchmark of this system might be the LNG bunker system with a bunker capacity of approx. 1000m3/hr.

4.2.3 Knowledge Gap

Although there is practical experience of mooring bunker vessels to the Sleipnir in- and nearshore, there is no experience yet of mooring such a vessel offshore during the LNG bunkering stage.
The particular Carbon Collectors vessel is not equipped with a DP2 system and thus there is a requirement to moor the vessel alongside the Sleipnir (leeside) using the mooring system proposed in section 4.2.2 (which needs to be defined in the project). Its behaviour therefore needs to be well understood. This require modelling and numerical analysis of the operations to be conducted offshore, aiming at calculating operational window during approach, offloading and departure. The design of a CO_2 offloading system shall be based on this calculated operational window with corresponding accelerations, forces, etc, to avoid the system becomes the weak link.

Modelling of a Carbon Collectors vessel mooring alongside the Sleipnir has not been included in the CC scope for MARIN modelling & analysis. In the project we need to discuss options to propose a CO_2 offloading system.

5 Offshore transfer of CO2 from ship to CO2-Geo-storage units

5.1 State-of-the-art

Offshore transfer of CO2 from a ship to a CO2 geological storage has not been done before. The state-of-the-art for this specific purpose is therefore non-existent. However, there are very relevant solutions for the transfer of fluids from a fixed offshore structure to a ship, such as those for loading oil tankers from an offshore tower loading unit, or for the transfer of LNG that should be considered state-of-the-art. Bluewater and Imodco are two suppliers of such systems.

5.2 What is needed for LNG-Zero

We want to understand the operability limits for a CO_2-Detachable Stern Vessel (DSV) as it moors to a fixed-bottom tower loading unit in Southern North Sea conditions and stays connected for a period long enough to offload approximately 4,000 tonnes of CO_2 in liquid form at relatively high pressure and temperature: 40 bar and 5°C. We also need to know what temperature variations we can expect in all elements of the connected system, from the onboard CO_2 storage vessels through the piping, pumps, hoses and wells to the geological storage reservoir.

5.3 Knowledge Gaps

Although there is practical experience mooring oil tankers to offshore structures (such as the Bluewater Advanced Loading Towers (Advanced loading towers - Bluewater Energy Services), there is no knowledge of mooring a Detachable Stern Vessel, such as designed by Carbon Collectors to an offshore Tower Loading Unit (TLU). This particular Carbon Collectors vessel is not equipped with a DP2 system and will "weathervane" around the TLU while moored. Also, the ship design is different from known oil tankers in the Southern North Sea so its behavior needs to be well understood. We require modelling and numerical analysis (single-body and multi-body frequency domain calculations) of the operations to be conducted offshore, aiming at calculating operational window during approach, offloading and departure. The sea going capabilities of the articulated barge should also be assessed and optimized in order to guarantee the best uptime.

Model tests are required for validation of the most relevant conditions identified with the numerical model. Model tests with the DSV / articulated barge in offloading configuration at the Tower Loading Unit (TLU) would need to be performed with a hawser and the tug propulsion activated such that the hawser remains tensioned. Dedicated tests can also be performed for tuning and improvement of a numerical model.

The transfer of liquid CO_2 from the Carbon Collectors DSV directly to the geological storage reservoir needs to be modelled in process flow models such as Hysis and OLGA in order to understand the system's operational limits and to determine the best offloading procedures.