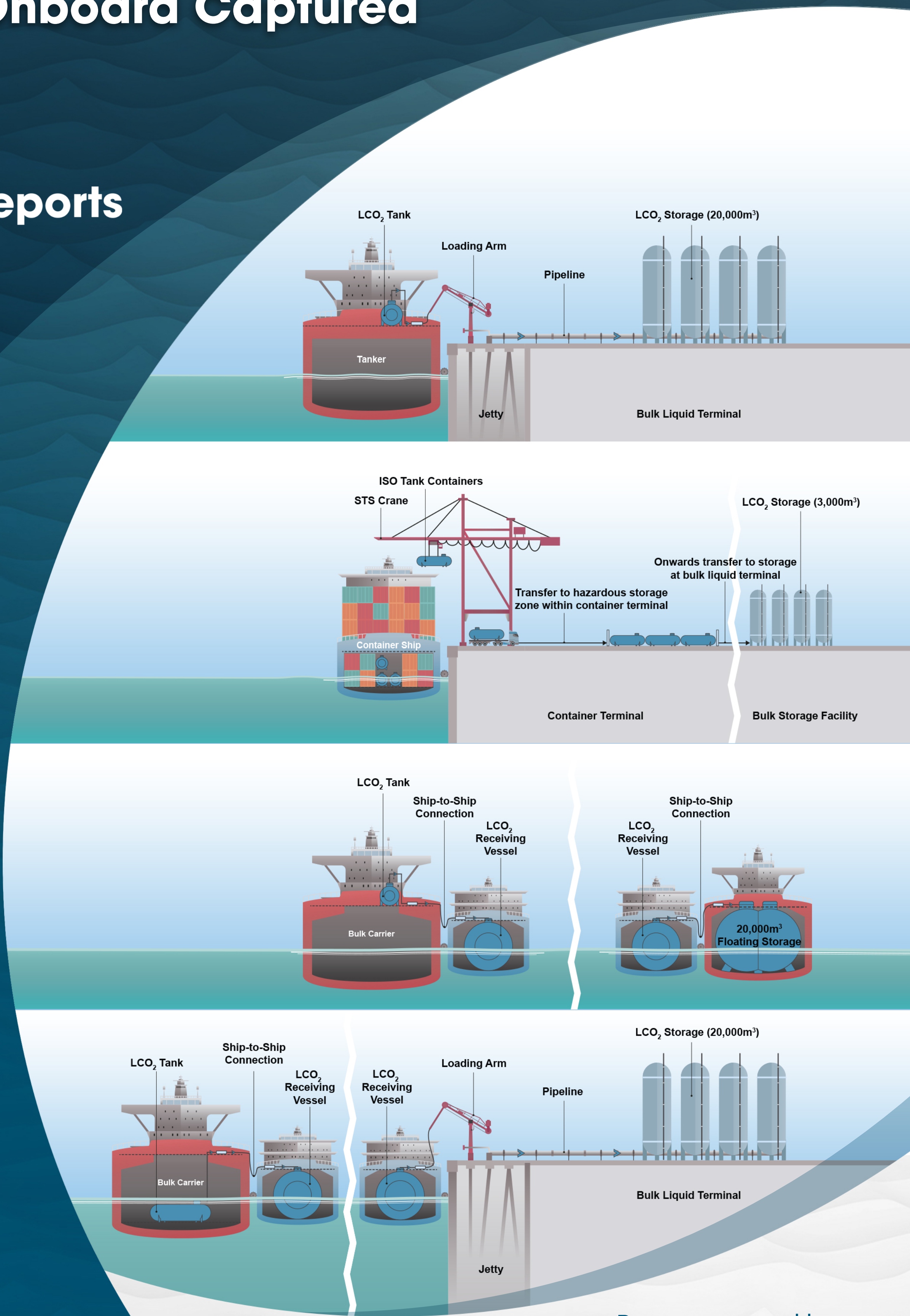
Concept Study to

Offload Onboard Captured CO_2

GCMD | reports



Commissioned by

Global Centre for MARITIME DECARBONISATION

Report prepared by

LR

ARUP

Contents

Appendices
(Available separately for download on GCMD's website)

Appendix A	LCO_2 Offloading Scenarios & Shortlisting of Concepts
Appendix B	Block Flow Diagrams (BFD) for the Shortlisted Concepts
Appendix C	Process Flow Diagrams (PFD) for the Shortlisted Concepts
Appendix D	HAZID Worksheets
Appendix E	SIMOPS Worksheets
Appendix F	QRA Assumptions Register
Appendix G	Project Aramis CO_2 Specifications

List of tables

List of figures

List of abbreviations

Abbreviation	Description
ACCE	Aspen Capital Cost Estimator
ALARP	As Low As Reasonably Practicable
ANSI	American National Standards Institute
API	American Petroleum Institute
APR	Air Purification Respirator
Ar	Argon
ASME	American Society of Mechanical Engineers
Bara	Absolute Pressure in Bar
Barg	Gauge Pressure in Bar
BCGA	British Compressed Gases Association
BFD	Block Flow Diagrams
BLEVE	Boiling Liquid Expanding Vapor Explosion
BOG	Boil-off Gas
BS	British Standards
BS EN	British Standards (European)
BV	Bureau Veritas
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCTV	Closed Circuit Television
CCUS	Carbon Capture, Utilisation and Storage
CGA	Compressed Gas Association
CH_4	Methane
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Critical Point
CSA	Canadian Standards Association
DG	Dangerous Goods
DN	Nominal Diameter
DNV	Det Norske Veritas
DTL	Dangerous Toxic Load
DP	Differential Pressure
EEA	European Economic Area

Abbreviation	Description
EEBD	Emergency Escape Breathing Devices
EN	European Standard
EOR	Enhanced Oil Recovery
ERC	Emergency Release Coupling
ERP	Emergency Response Plan
ERS	Emergency Release Systems
ESD	Emergency Shutdown
ETA	Event Tree Analysis
ETS	Emissions Trading System
EU	European Union
FCSU	Floating CO_2 Storage Unit
FCSU-i	Floating CO_2 Storage Unit with injection capability
FID	Final Investment Decision
FSS	Fire Safety Systems
GCMD	Global Centre for Maritime Decarbonisation
GHG	Greenhouse Gas
GHS	Globally Harmonized System
GWR	Guided Wave Radar
H_2	Hydrogen
H_2S	Hydrogen Sulphide
HAZID	HAZard IDentification
HFO	Heavy Fuel Oil
HP	High Pressure
HSE	Health, Safety and Environment
IBC	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
IEC	International Electrotechnical Commission
IFP	Invitation For Proposals
IGC	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels
IMDG	International Code for the Maritime Transport of Dangerous Goods
IMO	International Maritime Organization
IRV	Intermediate Receiving Vessel
ISM	International Safety Management Code

Abbreviation	Description
ISO	International Organization for Standardization
ISGINTT	International Safety Guide for Inland Navigation Tank-Barges and Terminals
ISPS	International Ship and Port Facility Security Code
K	Kelvin
LCO_2	Liquefied Carbon Dioxide
LED	Light-Emitting Diode
LFO	Light Fuel Oil
LNG	Liquefied Natural Gas
LOTO	Lock Out – Tag Out
LP	Low pressure
LPG	Liquefied Petroleum Gas
LR2	Long Range 2
LSIR	Location Specific Individual Risk
LVSC	Low Voltage Shore Connection
M/E	Main Engine
MARPOL	International Convention for the Prevention of Pollution from Ships
MDMT	Minimum Design Metal Temperature
MEA	Monoethanolamine
MEG4	Mooring Equipment Guidelines (4th Edition, 2018)
MLA	Marine Loading Arm
MOC	Management of Change
MP	Medium Pressure
MPA	Maritime & Port Authority of Singapore
MPS	Maritime Performance Services
MT	Metric Tonnes
N_2	Nitrogen
NACE	National Association of Corrosion Engineers
NDT	Non-Destructive Testing
NFPA	National Fire Protection Association
NH_3	Ammonia
NOx	Nitrogen Oxides
NOPSEMA	National Offshore Petroleum Safety and Environmental Management Authority
NPSH	Net Positive Suction Head
NTP	Normal Temperature and Pressure

Abbreviation	Description
O_2	Oxygen
OCCS	Onboard Carbon Capture and Storage
OCIMF	Oil Companies International Marine Forum
OPEX	Operational Expenditure
OSHA	Occupational Safety and Health Administration
PBU	Pressure Build-Up Unit
PEL	Permissible Exposure Limit
PFD	Process Flow Diagrams
PIC	Person In Charge
PMS	Preventive Maintenance System
PPE	Personal Protective Equipment
Ppm	Parts Per Million
PRV	Pressure Relief Valve
PSL	Product Specification Levels
PSV	Pressure Safety Valve
PTFE	Polytetrafluoroethylene
QA/QC	Quality Assurance / Quality Certification
QC/DC	Quick Connect / Disconnect Coupler
QRA	Quantitative Risk Assessment
RAG	Red-Amber-Green
ROB	Remainder on Board
RP	Recommended Practice
SCBA	Self-Contained Breathing Apparatus
SDS	Safety Data Sheet
SIGTTO	Society of International Gas Tanker and Terminal Operators
SIMOPS	Simultaneous Operations
SLOD	Significant Likelihood of Death
SLOT	Specified Level of Toxicity
SMS	Safety Management System
SO_2	Sulphur Dioxide
SOx	Sulphur Oxides
SOLAS	International Convention for the Safety of Life at Sea (SOLAS), 1974
SOPs	Standard Operating Procedures
SSL	Ship-to-Shore / Ship-to-Ship Link

Abbreviation	Description
STCW	International Convention on Standards of Training, Certification and Watchkeeping for Seafarers
STEL	Short Term Exposure Limits
StS	Ship-to-Shore / Ship-to-Ship
TDLAS	Tunable Diode Laser Absorption Spectroscopy
TLV	Threshold Limit Value
ToR	Terms of Reference
tpd	Tonnes-per-day
TRL	Technology Readiness Level
TtW	Tank-to-Wake
UK	United Kingdom
UK HSE	United Kingdom Health and Safety Executive
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
UPS	Uninterrupted Power Supply
USCG	United States Coast Guard
VLE	Vapour-Liquid Equilibrium
VTS	Vessel Traffic Services
WP	Working pressure

Executive Summary

Overview

The revised 2023 International Maritime Organization (IMO) greenhouse gas (GHG) strategy identifies revised levels of ambition for the international shipping sector: to reduce carbon intensity by at least 40% by 2030, compared to 2008 and to reach net-zero GHG emissions by or around, i.e., close to, 2050. To achieve these ambitions, the IMO GHG strategy emphasises energy-efficient ship designs and the adoption of zero or near-zero emission fuels and technologies.

However, achieving zero emissions from ships involves either replacing fossil fuels with low-carbon alternatives or mitigating emissions from existing fuels, both of which pose challenges. While progress has been made in developing viable alternative fuels, like green or blue methanol, ammonia and hydrogen, their widespread adoption across the shipping fleet will take time and can be costly.

Onboard carbon capture and storage (OCCS) emerges as a short to mid-term solution to reduce emissions during this transition. While carbon capture and storage (CCS) technologies have been established onshore for some time, OCCS for ships has only gained traction recently as a feasible approach to meet emissions reduction targets. Its successful adoption will require a compelling economic case, updated regulations, infrastructure development, and consensus on standards and guidelines.

This study aims to explore and define conditions for the storage and handling of onboard captured CO_2, as well as its offloading as liquefied CO_2 (LCO_2)[1] from ships to reception facilities. These facilities may include shore terminals, floating CO_2 storage units, or LCO_2 receiving vessels.

The effectiveness of OCCS for maritime decarbonisation hinges on successfully integrating carbon capture solution onboard ships and offloading the captured LCO_2 to the onshore carbon capture, utilisation and storage (CCUS) value chain.

Liquid CO_2 Characteristics and Hazards

The triple point, where the three phases (gas, liquid and solid) of a substance coexist in thermodynamic equilibrium, occurs for CO_2 at a temperature of -56.6 °C and pressure of 5.18 bara (absolute pressure in bar).

CO_2 can be liquefied at various pressures and temperatures between the triple point (5.18 bara, -56.6 °C) and the critical point (73.8 bara, 31.1 °C). Storage and offloading of CO_2 should be carried out in its liquid state for more efficient and economic operations as a result of its high density at these conditions.

The hazards of CO_2 include asphyxiation due to oxygen displacement and potential toxicity at higher exposure levels. Humans exposed to a CO_2 concentration of 3% in air for an hour may experience toxicological symptoms of headaches and those exposed to CO_2 concentrations of 17% in air for one minute may experience more pronounced toxicological symptoms and even death. While CO_2 is not classified as acutely toxic under the Globally Harmonized System (GHS), its toxicity depends on

[1] Liquefied carbon dioxide (LCO_2) is carbon dioxide which has been converted to liquid form by cooling or/and compression for storage and transportation purposes. The term ‘Liquid CO_2’ denotes the liquid phase of carbon dioxide.

concentration and exposure time. Some countries have defined threshold values within their health and safety protocols. The review of The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) by the IMO Sub-Committee on Carriage of Cargoes and Containers proposes amending the classification for “carbon dioxide (high purity)” and “carbon dioxide (reclaimed quality)” to include toxicity, alongside its recognition as an asphyxiant.

Other hazards of liquid CO_2 include boiling liquid expanding vapor explosion (BLEVE), danger of low temperatures causing frostbite and structural failure, impacts of impurities affecting equipment integrity and transport efficiency, challenges posed by water presence and solubility, and risks associated with proximity to its triple point leading to solidification and dry ice formation. Managing CO_2 impurities, water content and phase equilibrium is crucial for safe transportation, storage and integration into the CCUS value chain.

Onboard Storage of Captured CO_2

The existing literature on CO_2 properties, hazards, phase behaviour and CCS systems indicates that storing LCO_2 at low pressure (LP) of 5.7 to 10 bara at -54.3°C to -40.1°C (working pressure (WP): 8.0 bara at -50.0°C) or medium pressure (MP) of 14.0 to 19.0 bara at -30.5°C to -21.2°C (WP: 16.0 bara at -30.0°C) conditions as optimal for storing and handling onboard captured CO_2.

CO_2 can be liquefied at various pressures and temperatures between the triple point (5.15 bara, -56.6 °C) and the critical point (73.8 bara, 31.1 °C). Storage at MP conditions ensures safe operations away from triple-point conditions, mitigating the risk of dry ice formation whilst retaining LCO_2 at high density. Alternatively, to lower capital expenditure (CAPEX), it may also be stored at LP conditions. The choice of storage and transport in liquid phase is primarily a density consideration, with CCS value chain alignment dictating offloading in liquid phase. The liquefaction and storage of CO_2 under either LP or MP conditions are both viable options, considering the process energy intensity and the storage efficiency ($tonCO_2$/[$tonCO_2$ + ton tank]). Another option for storage is ISO tank containers, in which LCO_2 is stored at 18.0 to 24.0 bara (WP: 22.0 bara) and -25.0 °C to -20.0°C. Some may favour storage at LP conditions due to a higher density of liquid CO_2 and lower CAPEX, although finding the optimal balance away from the triple point for safe handling during offloading and transportation remains crucial.

Exploring the specifications of LCO_2 quality reveals the impacts of impurities on operations and provides insights into the anticipated requirements for offloading. Even minor impurity concentrations, such as water content of more than 50 parts per million (ppm) or non-condensable gases, such as hydrogen or nitrogen of more than 0.3% by volume, can cause storage tank and pipeline corrosion, form hydrates, increase compression power requirements, and jeopardise CO_2 storage and transport pipeline safety. The triple point is influenced by the presence of impurities, such as nitrogen more than 0.3% by volume, and must be accounted for in the system design.

Processing captured CO_2 to meet quality standards hinges on allowable impurity concentrations ensuring safe storage, offloading and transportation. The captured CO_2 will need to meet product specifications, which is dictated by the end use of the offloaded CO_2, whether for utilisation or geological sequestration. It will also need to meet the requirement specifications related to the handling of captured CO_2.

Materials suitability and containment types for onboard LCO_2 storage tanks, considering the temperature range and the presence of impurities, were evaluated. Semi-refrigerated Type C tanks (LP/MP conditions) and ISO tank containers emerged as the most feasible containment solutions for onboard LCO_2 storage.

Storage capacities were calculated to meet 12 – 20 days of voyage for a representative Panamax container ship, a Panamax bulk carrier and an LR2 tanker at a 70% capture rate, and to comply with CII regulations in 2023, 2024, and 2025. Initially, the shipping industry is not expected to pursue 100% carbon capture, and instead follows the decarbonisation regulatory obligations in designing OCCS capacities.

Considering these aspects, a design profile was established, outlining possible storage conditions, tank types, and capacities for the above-mentioned vessel types. This served as the foundation for subsequent study phases/stages.

Onboard Captured Liquefied CO_2 Offloading Concepts

The study shortlisted offloading concepts from a total of 162 possible permutations for the following variables:

1. Ship type – container ship / tanker / bulk carrier,
2. Onboard storage – above deck / below deck / above deck – cassette (ISO tank container),
3. Transfer type – ship-to-ship / ship-to-shore,
4. Intermediate storage – LCO_2 receiving vessel,
5. In port storage – LCO_2 carrier / floating CO_2 storage / shore storage, and
6. Conditions of storage – LP / MP / ISO tank container.

Finally, four offloading concepts were selected for this study:

Concept 1 – Ship-to-liquid bulk terminal,

Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel,

Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel, and

Concept 4 – Ship-to-terminal with ISO tank containers.

These four concepts represent the most practical and cost-effective solutions for near-term applications for offloading onboard captured and liquefied CO_2. Additionally, between them, the concepts cover the key offloading steps for a wider range of offloading solutions, so they can be used as building blocks to explore and inform design and operational considerations more broadly.

Design and Operation Standards for Offloading Liquid CO_2

An extensive scan was conducted to scrutinise the existing design and operational standards relevant for offloading LCO_2, focusing on the storage and offloading processes of CO_2 captured onboard ships. This in-depth analysis aimed to categorise standards into four key areas: machinery, piping, storage, and safety. The goal was to identify existing gaps that could impact the safe and efficient offloading of LCO_2 from onboard capture systems.

While the maritime sector lacks specific regulatory standards for onboard captured CO_2 systems, classification societies have taken strides in formulating rules and guidelines for ships equipped with these systems, instilling confidence in their installation and operation. Although the IGC Code, tailored for bulk liquefied gases, does not directly apply to onboard captured CO_2, it offers valuable insights into aspects, such as machinery, piping, storage, and safety.

Well-established onshore sectors, with their extensive experience in CCUS installations, also possess robust standards adaptable to the unique requirements of LCO_2 offloading from ships. Additionally, existing standards for liquefied petroleum gas (LPG) / liquefied natural gas (LNG), sharing similar characteristics with LCO_2, can serve as a blueprint for conceptualising efficient LCO_2 offloading arrangements. To bridge the identified regulatory gaps, leveraging pertinent LCO_2 standards from onshore sectors and drawing insights from LPG/LNG standards in both maritime and onshore sectors can offer viable solutions.

The significant gaps identified were:

- Standardisation of storage systems and storage conditions is needed. Requirements need to be defined for the characterisation of the LCO_2 captured onboard ships, noting different geological storage sites will have site-specific conditions (i.e., pressure, temperature and impurity type and its concentration), which the offloaded LCO_2 must match in order to enable CO_2 to be stored or used. Port reception facilities and ship operators will require knowledge of such conditions at the point of offloading.

- The International Convention for the Prevention of Pollution from Ships (MARPOL) Convention does not account for onboard captured CO_2 as a waste stream. Standards need to be set for measuring and recognising any collected and transferred LCO_2, as well as those for establishing monitoring, reporting and verification methods.

- Requirements for port reception facilities for the offloading of LCO_2 are needed.

- Competency and training standards are needed for personnel handling LCO_2 offloading from ships.

The majority of the above issues will likely be addressed by the IMO as OCCS gains traction in the maritime industry.

Design Principles and Guidelines for Offloading Liquid CO_2

Chapter 5 of the report aims to establish comprehensive design principles and guidelines governing the offloading of onboard captured LCO_2 to onshore and offshore storage facilities. As specific guidance on the design and use of offloading systems for onboard captured LCO_2 is currently lacking, this chapter consolidates foundational principles to drive the feasibility and advancement of onboard carbon capture. It covers several key areas:

- Detailed principles and guidelines for onboard captured LCO_2 offloading and storage terminal designs: ship-to-ship and ship-to-shore.

- Specifications for capturing and receiving vessel interfaces, ship-to-shore offloading requirements and associated safety equipment.

- The analytical methods and verification procedures to measure the quantity and quality of LCO_2 during custody transfer.

These principles and guidelines are founded on engineering experience, first principles, and insights from more established processes and build on existing standards governing LCO_2, LNG and LPG handling.

This chapter covers general design principles encompassing ambient design temperatures, process design temperatures, design pressure, pressure drop, testing requirements and isolation requirements. It describes principles and methods for measuring both the quantity and quality of offloaded LCO_2 and its storage. The chapter extensively elaborates on design principles and guidelines across various areas including gas detection, marine infrastructure, metocean conditions, loading arms, flexible hoses, pumps, pipelines, bulk storage tanks, intermediate LCO_2 receiving vessel and floating CO_2 storage. These insights aim to steer the design process and enhance operational reliability. Evolving new technologies for OCCS and LCO_2 handling might establish different LCO_2 quality standards and requirements in the future, necessitating adaptations in the design of offloading systems accordingly. Safety measures and equipment including hazards to personnel, use of appropriate personal protective equipment (PPE), boil-off gas (BOG) equipment, emergency shutdown devices (ESD) and emergency release systems (ERS) are also addressed.

Procedures for Offloading Liquid CO_2

Chapter 6 outlines the operating procedures and the necessary steps in the LCO_2 offloading operation with a focus on minimising risks and optimising performance. Safety measures are incorporated in the procedures and environmental protection measures enumerated. They include general requirements, such as establishing an LCO_2 offloading plan, conducting risk assessments, establishing communication protocols, and defining safety, security, and marine zones. Additionally, this chapter outlines the responsibilities of personnel involved in offloading operations.

The various stages of LCO_2 offloading from ship-to-ship or ship-to-shore — planning, pre-offload, transfer, and post-transfer phases — are detailed, along with their specific requirements. Procedures for loading/unloading ISO tank containers, encompassing lift planning, equipment readiness, personnel competence, and lift execution, are described thoroughly.

Additionally, the chapter outlines environmental protection measures, providing guidance on mitigating CO_2 release during offloading operations.

Finally, the chapter details emergency response procedures for various scenarios like extreme weather, blackout, collisions, over-pressurisation, and personnel injury. It emphasises the significance of an emergency response plan (ERP), encompassing crucial actions, such as raising alerts, initiating shutdown protocols, establishing communication, planning evacuations, defining procedures, locating protective gear, outlining personnel duties, and conducting drills. This structured framework can ensure a coordinated and effective response to LCO_2 release incidents, prioritising safety, environmental protection, and operational integrity. It concludes by offering typical emergency response examples aligned with ERP guidelines.

Safety Studies

Safety studies comprising a hazard identification (HAZID) study, a simultaneous operations (SIMOPS) study and a coarse quantitative risk assessment (QRA) study were carried out for the four shortlisted offloading concepts.

HAZID study

The aim of the HAZID study is to identify and risk assess the hazards associated with the four concepts. Given that this is a conceptual study, the HAZID also aims to identify potential engineering / maritime /

logistic factors to be considered for the subsequent project phases. Due to the highly conceptual nature of the offloading concepts and the various underlying assumptions affecting risk evaluation, no risk ranking was performed at this stage in the HAZID process. Risk ranking can be performed with this study as a basis when details of vessels and specifications on concept design are available.

A total of 131 scenarios were identified, with a number of concerns related mainly to the safety, operational and feasibility aspects of the LCO_2 offloading concepts. Some of the common concerns arising from the LCO_2 offloading concepts included:

- Causes resulting in loss of containment of LCO_2 and subsequent dispersion of a cold, dense CO_2 cloud or the development of cold temperature zones.
- Incompatibilities between merchant vessels and LCO_2 receiving vessels / receiving terminals (i.e., mooring loads/arrangement, weather profile at the shortlisted locations, berthing and fendering requirements, alignment of vessels, type of transfer equipment – loading arm or hoses, location of cargo transfer manifold, vapour return capabilities, purging capabilities, design pressure, operational & safety philosophy, etc.).
- Impurities in LCO_2 which can affect storage conditions and even possibly, the materials selection for the LCO_2 offloading system.
- Unfamiliarity with LCO_2 offloading processes, especially when LP/MP or MP/LP interface is involved, coupled with inexperienced crew onboard merchant vessels.
- Undefined drying and purging requirements pre/post LCO_2 offloading operations.

Logistical concerns were raised for ship-to-terminal with ISO tank containers. Container ships with OCCS using different fuel types may have different impurity type and levels in the captured CO_2. Consequently, the container terminal might face challenges swapping empty LCO_2 ISO tank containers with the container ships unless they adhere to the same standard specifications and do not surpass a uniformly defined LCO_2 impurity level standard. Another concern raised was the expected voyage duration of a container ship and the BOG holding time of the ISO tank containers. The holding time may range from 30 to 90 days, depending on the environmental conditions and the initial filling conditions. Typically, ships may fill up all LCO_2 ISO tank containers onboard and swap them at one terminal in one go. However, with an expectation of having 10-15 LCO_2 tanks fully filled before the next tank swapping, there is a risk that the tanks initially filled may exceed the BOG holding time if offloading is beyond 30 days.

Throughout the HAZID discussions, it became evident that there is work yet to be completed to facilitate LCO_2 offloading concepts. One of the primary concerns emphasised across all offloading concepts was the impurities of LCO_2. Impurities not only pose a safety risk due to materials incompatibilities within the supply chain, but the type and concentration of impurities may also impede the progress of OCCS adoption. This is particularly significant as end-users may have different LCO_2 impurity specifications.

In total, 54 recommendations were made to address the abovementioned concerns, which should be taken forward into the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

SIMOPS study

A HAZID study for SIMOPS was conducted to further understand the impact of carrying out concurrent activities alongside LCO_2 offloading operations.

The SIMOPS study also covered the four LCO_2 offloading concept designs detailed in this study. A total of 35 concurrent activities scenarios were identified. Some of the significant concerns raised include:

- Potential for dropped objects from concurrent activities. This may result in damage to the LCO_2 offloading equipment and pipeline while LCO_2 transfer is in progress, leading to a subsequent loss of LCO_2 containment. Dropped objects and loss of LCO_2 containment will also be a risk for the personnel involved in the SIMOPS.
- Loss of containment of LCO_2 during LCO_2 offloading operations affecting the other concurrent activities in the vicinity (especially those at lower elevations).
- Loss of containment of alternate fuels (i.e., LNG/LPG/Ammonia/Methanol) during simultaneous fuel bunkering.
- Manpower designation and distribution if multiple ship-to-ship (StS) operations are carried out at the same time.

The SIMOPS discussion primarily focused on concept 1 (ship-to-liquid bulk terminal), concept 2 (ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel and concept 3 (ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel).

Current regulations, such as the International Code for the Maritime Transport of Dangerous Goods (IMDG), classify CO_2 as a non-flammable, non-toxic gas. Many terminals handle LCO_2 ISO tank containers as ordinary containers during transfers. Consequently, there are no significant impact or concerns regarding concurrent operations when LCO_2 ISO tank containers are being transferred under concept 4 (ship-to-terminal with ISO tank containers). The transfer operation is considered the same as that for other ordinary containers. The offloading of LCO_2 from the ISO tank containers at the bulk storage facility is also considered a normal operation for the storage terminal. The requirements for SIMOPS for storage terminals vary based on the chemicals/materials they are storing, which will be covered by their own set of terminal operating procedures. Hence, the LCO_2 offloading aspects of concept 4 were not further assessed.

In total, there were 20 recommendations raised in the SIMOPS workshop addressing the abovementioned concerns, such as controlling the operating envelope of cranes, providing alarms for loss of containment of LCO_2, carrying out gas dispersion study, which should be taken forward in the next phase of the project or should be considered by interested parties that are further developing OCCS/LCO_2 offloading concepts.

QRA study

A coarse QRA study was conducted to assess the overall risk arising from the shortlisted LCO_2 offloading concepts at a hypothetical anchorage location and a hypothetical onshore bulk liquid storage terminal. The Offloading concept 3 (ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel) was selected to be the representative concept due to increased complexity over the other offloading concepts.

Individual risk contours were produced to provide a visual representation of the potential risks within the areas surrounding LCO_2 offloading operations. Several assumptions had to be made, including the assumption that LCO_2 offloading operations will occur four times a week (208 times a year) at anchorage, and once a week (52 times a year) at the terminal with each offloading operation assumed to take eight hours. The QRA study conclusions are shown in Table ES 1 below.

Table ES 1 – QRA study conclusions

Location	Tolerable Risk Criteria	Risk result
Anchorage This is the location where the merchant vessel is expected to offload LCO_2 to the LCO_2 receiving vessel via ship-to-ship transfer.	1×10^{-4}/yr for personnel risk. The risk criteria is adapted from the UK HSE ALARP framework whereby risk levels greater than 1×10^{-4}/yr for the public group is considered to be intolerable.	The 1×10^{-4}/yr LSIR contour corresponding to the tolerable risk criteria for personnel onboard vessels or in the vicinity is not reached. Hence, the risk presented is lower than the specified criterion.
Bulk Liquid Storage Terminal This is the location where the LCO_2 receiving vessel is expected to berth to offload LCO_2.	1×10^{-4}/yr for personnel risk. The risk criteria is adapted from the UK HSE ALARP framework whereby risk levels greater than 1×10^{-4}/yr for the public group is considered to be intolerable.	The 1×10^{-4}/yr LSIR contour corresponding to the tolerable risk criteria for personnel onboard the vessel or in the vicinity of the LCO_2 offloading facility is not reached. Hence, the risk presented is lower than the specified criterion.

ALARP – As Low As Reasonably Practicable; LSIR – Location Specific Individual Risk

The coarse QRA study for LCO_2 offloading is based on a concept design; key assumptions were made about the frequency of LCO_2 offloading operations, the location and layout of the LCO_2 offloading facilities, as well as the safety margin used during parts count of the LCO_2 offloading equipment, which would impact the outcome of the QRA. The study also conservatively assumed that any loss of containment would result in a horizontal dispersion of toxic cloud, though it is possible that some LCO_2 is released into the sea for certain scenarios, which may dissolve in water and thus, reducing the amount of toxic gas being dispersed.

Apart from the assumptions that impact QRA, the risk criteria also play an important role as they can vary depending on the risk appetite of the local regulatory authority or operating company, whichever is more stringent. Some examples may include additional risk criteria for different categories of land zoning, such as residential and industrial., which are usually meant for onshore applications.

While the introduction of representative LCO_2 offloading concept (ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel) is within the tolerable risk criteria, the coarse QRA findings are only associated with the LCO_2 offloading concept and do not take into consideration the potential existing risk profile of the vessels or the bulk liquid storage terminal, in the event they are storing and handling other hazardous materials. Therefore, it is also recommended that risk integration is considered in the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

Operating Personnel Competency Standards

A challenge in offloading LCO_2 from ships will be to ensure the competence of personnel engaged with handling LCO_2 onboard ships. Accordingly, an analysis was conducted to assess the human-related aspects of storage and handling of LCO_2. This analysis led to the creation of competency standards for shipboard and shoreside operating personnel interfacing with LCO_2. The International Convention on

Standards of Training, Certification and Watchkeeping for Seafarers (STCW) takes precedence and the matrix proposed in this study may be used as a guideline.

The competency standards are presented in this report via two frameworks. The first framework, "Proposed Competencies for Handling Captured Liquid CO_2 Onboard Ships", focuses on shipboard personnel and uses the existing STCW requirements for minimum standards of competence with the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels (IGF Code) as a starting point. Other sections of STCW Chapter V for Tankers and for Liquefied Gas Tankers competency and training standards also serve as an input for creating the LCO_2 shipboard framework. The framework is organised in the standard tabular format used in STCW.

A second framework, "LCO_2 Handling Competency Information – Shipboard and Shoreside Personnel", has been created as a supplement to the proposed seafarers' standards outlined above. The purpose of this second framework is to provide further details on seafarer's competencies, as well as outline similar information for shoreside personnel and identify interactions, interfaces and commonalities for all involved with LCO_2 operations.

In addition to competency standards, this report also highlights how prior experience of shipboard personnel can impact the speed of developing competencies for LCO_2. The report also emphasises the importance of coordination and collaboration of all organisations involved to ensure efficient, safe and environmentally sound operations.

The competency frameworks in this report should be used to design and refine appropriate company training requirements to mitigate captured LCO_2 risks and enhance safety by ensuring personnel achieve the desired level of competency for their intended roles. Users of this report should view the competency recommendations provided here within the context of their existing internal and regulatory training programs. Each operating company will need to determine the changes required within their existing programs to accommodate captured LCO_2 related operations.

Readiness of Current Infrastructure for Liquefied CO_2 Offloading

A review was conducted for the readiness of current infrastructure for LCO_2 offloading (i.e., facilities that can be used or with modifications or as new assets) relating to the four offloading concepts defined in Chapter 3.

There are limited publicly available examples of existing terminals handling CO_2 as a product in ports. Nonetheless, the concepts developed as part of this study aim to integrate offloading of onboard captured LCO_2 with existing port infrastructure as far as practical. The potential remains for modifying or upgrading existing port facilities for pilot projects or near-term applications.

From the work completed as part of this review, the following conclusions were drawn:

- LCO_2 offloading is an industry in its infancy. It currently lacks operational examples that work in a manner similar to the premise of this study.
- Several ports and facilities are currently developing infrastructure projects, with some in the conceptual design stage and others at the detailed design and execution levels. These projects involve a diverse range of stakeholders from the energy, manufacturing, and maritime industries.
- Northern Lights is the furthest along project for large-scale LCO_2 offloading at a jetty or port facility for a new/greenfield site. The construction of the receiving terminal and storage tanks is

currently in progress with operations expected to commence in 2025. However, a key driver for success of the Northern Lights project is the acceptance of this initiative and the brownfield adaptation of existing ports, from where LCO_2 will be sent to the receiving terminal.

- There are commercial facilities operational that handle food-grade LCO_2 at ports. Currently, only four to five ports regularly handle food grade CO_2 from ships with storage capacity around 1,200 – 1,800 ton. However, this is a specialised industry and is not directly applicable to the schemes proposed as part of this study, due to differences in specification, impurities and quantities involved.

- The complexity of port operations for offloading LCO_2 is a key concern for port facilities. The impact of introducing LCO_2 offloading on port efficiency and operational performance needs to be considered. SIMOPS is one way to minimise impact on the current port operational performance but SIMOPS necessarily introduces coordination complexities. Space constraint is a further issue; available land is a highly valued asset and port operators may not have space for LCO_2 storage infrastructure. These issues need to be addressed to convince port authorities on the viability of these schemes.

- Modifications required to infrastructure at existing bulk liquid terminals are dependent on the type of product and size range of vessels currently handled at the facility.

    - Concept 1 (ship-to-liquid bulk terminal) does not require major modification to jetty and berth infrastructure as tanker vessels will offload LCO_2 at the bulk liquid terminal where they discharge their main liquid cargo.

    - Concept 3 (ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel) is likely to require modification of jetty and berth infrastructure due to a difference in dimensions between an LCO_2 receiving vessel and other vessels that a bulk liquid terminal is designed for.

    - Concept 4 (ship-to-terminal with ISO tank containers) requires limited modifications to a container terminal; provision should be made for LCO_2 offloading 'hazardous product zone' for the storage of LCO_2 ISO tank containers at the port facility.

- Concept 2 (ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel) uses an LCO_2 receiving vessel and floating CO_2 storage:

    - Intermediate receiving vessels and floating storage are systems that are used today with other liquefied gases.

    - Existing LCO_2 carriers could be repurposed for use as a LCO_2 receiving vessel or floating CO_2 storage although they are unlikely to have the optimised capacities for the expected operational profiles.

CAPEX and OPEX Models for Cost Estimation of Infrastructure

Capital expenditure (CAPEX) and operational expenditure (OPEX) models were developed for each of the four offloading concepts outlined in this study. Both CAPEX and OPEX models are to a Class 5 level (-50%/ +100%). The estimates given within this report are intended for cost information purposes and are not an indication of business plan feasibility. The scope of the CAPEX costs and OPEX estimation is the offloading infrastructure, intermediate LCO_2 receiving vessel and onshore storage or floating CO_2 storage for each concept. The CAPEX models do not consider the cost of the onboard carbon capture system and necessary storage tanks onboard the merchant vessel. The OPEX models do not consider the cost of the fuel for the intermediate LCO_2 receiving vessel (IRV) and the floating CO_2 storage unit (FCSU).

The results of the CAPEX estimate are shown in Table ES 2 below. The base case of the CAPEX models assumes the purchase of a new IRV for concepts that deploy one such vessel. The alternative case assumes the purchase of a pre-owned IRV for cost savings. The FCSU cost is considered as new building cost for both base and alternative case as there are no existing vessels suitable to act as an FCSU today.

Table ES 2 – CAPEX estimates

	Base Case (Million USD)	Alternative Case (Million USD)
Concept 1 – Ship-to-liquid bulk terminal	$166	-
Concept 2 – Ship-to-FCSU with intermediate LCO_2 receiving vessel	$178	$141
Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel	$244	$207
Concept 4 – Ship-to-terminal with ISO tank containers	$33	-

A high-level breakdown of CAPEX estimate for each concept design is detailed in Table ES 3 below.

Table ES 3 – Breakdown of CAPEX estimates

	Shore Eqpmt. (M USD)	FCSU Eqpmt. (M USD)	Ship Eqpmt. (M USD)	IRV Eqpmt. (M USD)	Total Eqpmt.(1) (M USD)	Direct Field(2) (M USD)	Indirect Field (M USD)	Non-Field (M USD)
Concept 1	$90	-	$0.26	-	$96	$114	$9.2	$43
Concept 2	-	$3.5(3)	$0.26	$4.2(4)	$2.2	$126(5)	$1.3	$50
Concept 3	$90	-	$0.26	$4.2(4)	$97	$169	$9.8	$66
Concept 4	$13	-	$2.4	-	$16	$21	$2.5	$9.6

Notes: Eqpmt. Stands for equipment.
(1) Includes design allowance
(2) Includes total equipment cost
(3) FCSU equipment cost excluding the marine loading arm cost is included in direct field cost
(4) IRV equipment cost is included in direct field cost
(5) Includes IRV cost of USD 52M and FCSU cost of USD 68M. For alternative case, second-hand IRV cost is taken as USD 15M.

The results of the OPEX estimate are shown in Table ES 4 below. The OPEX for onshore operations is based on Arup's internal projects and a percentage of CAPEX (approximately 5%). For the onshore costs of concept 1 (ship-to-liquid bulk terminal) and concept 3 (ship-to-shore terminal with intermediate LCO_2

receiving vessel), direct costs for the shore facilities are taken from concept 1 and rounded to a value of USD 120M. For concept 4 (ship-to-terminal with ISO tank containers), a rounded direct cost of USD 25M is used. The OPEX for intermediate LCO_2 receiving vessel and floating CO_2 storage unit have been estimated to be similar to the vessel's ship management costs.

Table ES 4 – OPEX estimates

	Annual Operations Cost (Million USD)
Concept 1- Ship-to-liquid bulk terminal	5.5
Concept 2- Ship-to-FCSU with intermediate LCO_2 receiving vessel	11.4
Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel	10.3
Concept 4 – Ship-to-terminal with ISO tank containers	1.0

A high-level breakdown of OPEX estimate for the different concept is detailed in Table ES 5 below.

Table ES 5 – Breakdown of OPEX estimates

	IRV (Million USD)	FCSU (Million USD)	Onshore (Million USD)
Concept 1	-	-	\$5.54
Concept 2	\$4.74	\$6.64	-
Concept 3	\$4.74	-	\$5.54
Concept 4	-	-	\$1.02

Notes: The IRV and FCSU operations costs exclude fuel costs.

Ranking the Operability of Concepts

The operability of each concept was assessed against various criteria, including impact on the host vessel’s operations, scalability, costs, ease of operation, safety and technology readiness. For this exercise, operability is defined as the ability of an offloading concept to achieve a beneficial operation considering the aim of decarbonising marine vessels at scale. The benefits are generally categorised around cost-effectiveness and decarbonisation.

Given the influence of the end user on the environmental impact of onboard carbon capture technology, the applicability of each concept to transfer LCO_2 having varying levels of impurity has also been assessed separately. Four end uses were considered in the context of the offloading concepts:

- Sequestration – >95% CO_2 purity,
- Feedstock for synthetic fuels production – >95% CO_2 purity,

- Medical use – >99.5% CO_2 purity, and
- Food/beverage – >99.9% CO_2 purity.

Concepts operating with LCO_2 in bulk (1, 2 and 3) are better suited for sequestration and the production of synthetic fuels, and the concept of ISO tank containers (4) is better suited for offloading of higher grades of CO_2.

The applicability of the purity level of the LCO_2 from the onboard carbon capture system requires an assessment of end use and processing requirements together. For higher purity requirements, the onboard carbon capture system will be more complex and will consume more power. If the end use CO_2 purity standard is low but still meets onboard processing requirements, it is likely to minimise the impact on the processing equipment onboard the host vessel.

The multi-criteria assessment of the LCO_2 offloading concepts considered the categories of cost-effectiveness, ease of operation, safety and technology readiness, with results shown in Table ES 6 below.

Table ES 6 – LCO_2 concept operability ranking

Operability Ranking	Concept
1st	**Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel** – FCSU with IRV will be able to receive multiple parcels and benefits from the increased flexibility for parcel size and offloading rates from the merchant ship, made possible by the IRV. This concept enables highest possible offloading rate and also the highest scalability.
	Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel – Bulk terminal with intermediate vessel is tied with Concept 2, where advantages of onshore storage over the FCSU concept are cancelled out by the additional complexity of jetty transfer and its availability.
2nd	**Concept 4 – Ship-to-terminal with ISO tank containers** – Offloading ISO tank containers is more flexible and has minimal infrastructure requirements. However, its lack of scalability results in it being a less favourable option compared to Concepts 2 and 3. The main opportunity for this concept will be in the pilot stage.
3rd	**Concept 1 – Ship-to-liquid bulk terminal** – Simpler offloading than concepts 2 and 3 due to a smaller number of stages. However, OPEX is relatively high compared to other concepts in terms of cost per unit of CO_2 offloaded. This concept relies on jetty availability and the jetty opportunity cost makes it less favourable.

Although not ranked the highest as a scalable solution for the mid-term (five to 10 years range), concept 4 is the most 'pilot ready' concept today. However, the lack of scalability could disqualify it as a potential pilot. The barriers posed by scalability versus requirement for proof of concept should be evaluated prior to conducting any pilot.

Policy and Regulations Regime

The availability of a regulatory framework for offloading LCO_2 from ships is essential for the inclusion of the onboard captured CO_2 in the carbon capture usage and sequestration (CCUS) supply chain, and its seamless transfer to onshore and offshore storage and/or utilisation facilities.

The regulatory and policy frameworks of several countries related to CCS were investigated and reviewed. The countries were selected based on their potential for early infrastructure development for offloading LCO_2 and included the United Kingdom (UK), the European Union (EU), the United States of America (USA), Singapore, China, Japan, Korea and Australia. Additionally, the regulatory picture at a domestic level for the Netherlands, Denmark, Iceland and Norway (as part of European Economic Area (EEA)) was also explored to provide additional context. The intent of the review was to explore the regulatory readiness, either enabling or restricting LCO_2 offloading from ships. Furthermore, key issues at an international level were summarised, with the overall aim of identifying regimes that would allow this operation to take place within their national jurisdiction. This review and investigation were conducted using the most up-to-date information available as of January 2024.

For each country/region the following was explored:

- Linkage to the international policy and regulatory landscape, specifically the London Convention and London Protocol governing CO_2 transfer between countries.

- The general CCUS policy landscape – which could provide enabling conditions and pathways for new regulation – and any considerations of maritime transport of CO_2 or onboard captured LCO_2.

- A high-level picture of regulation for Health, Safety and Environment (HSE) risk management, pertinent to LCO_2, noting this is often a complex landscape that would require project-specific considerations.

The policy and regulatory landscape for offloading onboard captured LCO_2 is currently immature. Notably, MARPOL Annex VI addresses air pollution from ships but does not account for CO_2 as a waste stream. IMO guidelines on lifecycle GHG intensity of marine fuels (LCA guidelines) account for OCCS in the tank-to-wake (TtW) emissions factor calculations, but the methodological guidance on how the captured CO_2 is accounted for is yet to be developed. Furthermore, requirements for port reception facilities for LCO_2 offloading need to be established. While the London Protocol provides a regulatory framework for CO_2 transport and related carbon credits between countries, it presently does not cover the transfer of CO_2 captured in international waters to a country. Potentially, future amendments to the London Protocol could support the offloading of LCO_2 captured in international waters.

The lack of robust regulatory frameworks and policies may lead to a delay in the development, implementation and commercialisation of OCCS. On the other hand, the EU Emissions Trading System (ETS) applicable to maritime transport from January 2024 and IMO's potential implementation in 2027 of a market-based measure may incentivise OCCS adoption and LCO_2 offloading infrastructure development. The EU ETS puts a carbon price on CO_2 emissions and shipping companies will need to surrender EU Allowances, to cover 40% of their fleets' 2024 $TtWCO_2$ emissions. By 2027, they will need to surrender allowances for all emissions. It is not needed to surrender allowances if the CO_2 is captured onboard and permanently stored or utilised in accordance with the legislation requirements. The IMO's potential market-based measure incorporating a technical element and an economic element will also put a carbon price on CO_2 emissions. Though the specifics of the scheme are yet to be worked out, it is expected to be in place from 2027 onwards.

Some countries, including the UK, USA, and select European nations, have demonstrated a more active focus on CCUS policy, potentially leading to enabling regulatory, policy, and commercial conditions for offloading onboard-captured CO_2 over time. Generally, in the short term (up to 5 years from now), CCUS policy largely concentrates on sequestering captured CO_2, and in the medium term (between 5 and 10 years from now), on receiving bulk imports of CO_2. There could be an opportunity to influence policymakers to consider including onboard-captured CO_2 as part of this picture. Two regions (China and

South Korea) have regulatory frameworks under development for international transport of captured CO_2.

The regulatory landscape concerning HSE considerations related to offloading is intricate and often site-specific. Nevertheless, the existing HSE framework in many instances is likely to accommodate offloading requirements. While HSE considerations could impact the feasibility of offloading onboard captured CO_2, this aspect needs careful assessment for individual projects.

1. Introduction to Liquid CO_2 and Onboard Carbon Capture Systems

1.1 Overview

The revised 2023 International Maritime Organization (IMO) greenhouse gas (GHG) strategy identifies revised levels of ambition for the international shipping sector: to reduce carbon intensity by at least 40% by 2030, compared to 2008 and to reach net-zero GHG emissions by or around, i.e., close to, 2050. These levels of ambitions are envisioned to be attained through the implementation of energy-efficient ship designs and the adoption of zero or near-zero emission fuels, technologies and energy sources.

Reducing zero emissions from ships requires either replacing the fossil fuels powering the majority of the shipping fleet with zero or near-zero carbon alternative fuels, or mitigating the emissions produced by these fuels, or a combination of both pathways to reach the ultimate goal of net-zero emissions.

There has been significant progress in the development of viable zero or near-zero emission fuels for the shipping industry, such as methanol, ammonia (NH_3) hydrogen and biofuels. Despite their viability and technological readiness, widespread deployment of these low-carbon fuels to cover the entire shipping fleet will take considerable time, and converting existing vessels can be prohibitively expensive.

Urgency exists within the shipping industry to adopt solutions aligned with the IMO GHG strategy milestones. Onboard carbon capture and storage (OCCS) emerges as a short to mid-term solution to reduce tank-to-wake (TtW) emissions while the low-carbon fuels are deployed at scale on ships and can be the potential differentiator that facilitates the maritime industry in achieving net-zero greenhouse gas emissions.

While carbon capture and storage (CCS) has been a mature technology onshore for over 50 years, the concept of OCCS for ships has just gained momentum as a viable approach for the shipping industry to meet its carbon emissions reduction targets. OCCS has recently reached a technological readiness level that allows immediate extension of the existing asset lifetime within the evolving regulatory framework.

Successful adoption of OCCS hinges on establishing compelling economic cases for various stakeholders in the supply chain. Regulations must be updated to address practical deployment challenges. Substantial infrastructure scaling and investment are needed, and consensus is required on a limited number of onboard and offloading solutions to establish industry standards that generate the necessary economies of scale and scope for economic viability.

This study aims to explore and define the conditions for handling and storing of captured CO_2 onboard, as well as its offloading as liquefied carbon dioxide (LCO_2) from ships to reception facilities. These facilities may include shore terminals, floating CO_2 storage units, or LCO_2 receiving vessels.

The effectiveness of OCCS as a decarbonisation pathway in the maritime sector depends on successfully integrating the OCCS onboard ships, and more importantly, connecting the offloaded LCO_2 to the onshore carbon capture, utilisation and storage (CCUS) value chain.

1.2 Characteristics of CO_2

CO_2 is a colourless and odourless gas, and being fully oxidised is neither reactive nor flammable. [1]

CO_2, depending on the temperature and pressure conditions, can exist in either gas, liquid or solid phases or as a supercritical fluid.

At atmospheric pressure conditions, CO_2 can exist only in the gaseous or solid phases, and it means that:

- At constant atmospheric pressure conditions, with a rise in temperature above -78.1 °C, CO_2 from solid phase transforms directly into the gaseous phase without entering the liquid phase, in a process known as sublimation.
- Conversely, at constant atmospheric pressure conditions with a drop in temperature below -78.1 °C, CO_2 transforms from gaseous state to solid state forming dry ice, in a process known as deposition.

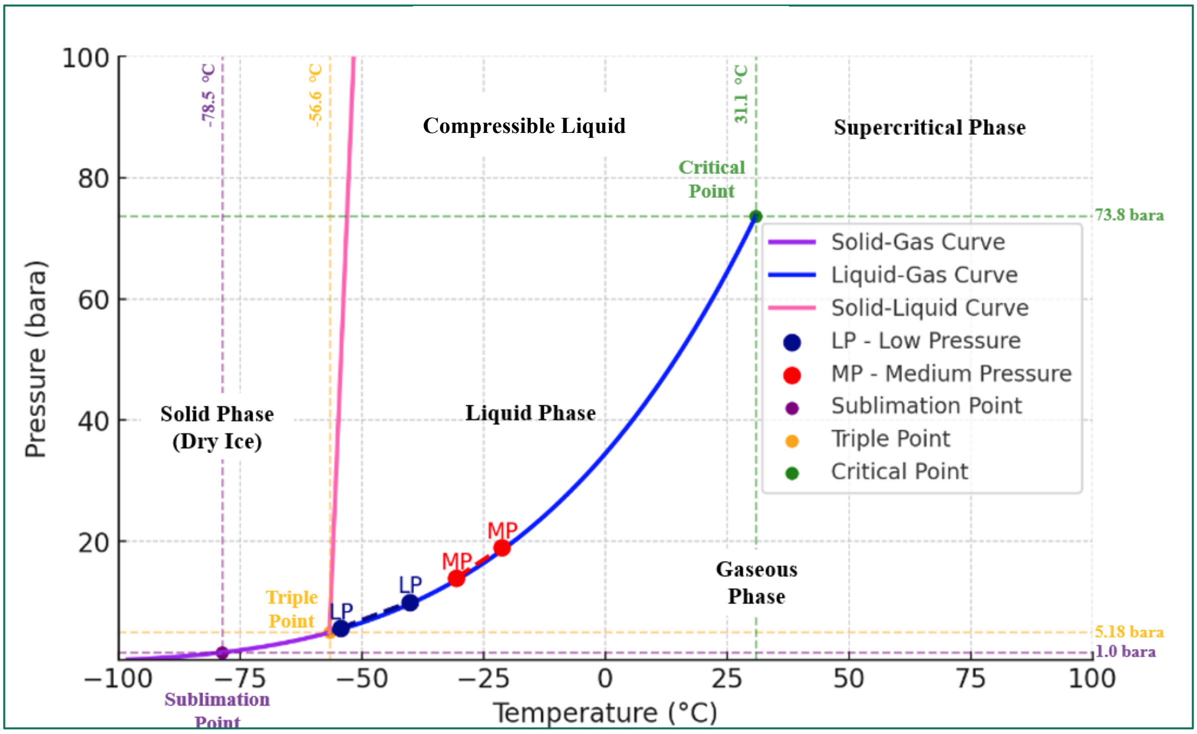


Figure 1.1 – CO_2 phase diagram (adapted) [2]

CO_2 exists as a supercritical fluid above its critical temperature and pressure of 31.1°C and 73.8 absolute pressure in bar (bara). In the supercritical phase, CO_2 exhibits the density of a liquid and viscosity of a gas.

The triple point for CO_2 is where the three phases of gas, liquid and solid coexist in thermodynamic equilibrium, and these conditions occur at a pressure of 5.18 bara and temperature of -56.6 °C

CO_2 can be liquefied at various pressures and temperatures between the triple point (5.18 bara, -56.6 °C) and the critical point (73.8 bara, 31.1 °C) along or above the liquid-gas curve shown in blue in figure 1.1.

1.3 Liquid CO_2 Properties

In order to carry out the offloading process according to the concepts presented in Chapter 3, the properties of liquid CO_2 need to be understood for safe and efficient offloading. The following section outlines properties that a designer should consider when specifying equipment and procedures for handling of liquid CO_2.

Storage and offload of CO_2 must be carried out in its liquid state for efficient and economic operations as a result of its high-density conditions. As observed in Figure 1.1, the liquid region of CO_2 lies within a defined temperature and pressure range.

The target conditions during storage and offload of liquid CO_2 may be low pressure (LP) condition (5.7 to 10.0 bara at -54.3°C to -40.1°C) or at medium pressure (MP) condition (14.0 to 19.0 bara at -30.5°C to -21.2°C). Targeting these ranges ensures safe operations away from the triple-point condition, mitigate dry ice formation whilst retaining liquid CO_2 at high-density.

A summary of the physical and chemical properties of CO_2 is presented in Table 1.1.

Table 1.1 – CO_2 physical and chemical properties

Property	Value
Molecular weight	44.01 g/mol
Sublimation point	-78.5 °C
Triple point pressure	5.18 bara
Triple point temperature	-56.8 °C
Density, liquid at 5.7 to 10 bara at -54.3°C to -40.1°C	1170 – 1117 kg/m^3
Density, liquid at 14 to 19 bara at -30.5°C to -21.2°C	1078 – 1037 kg/m^3
Density, liquid at 18 to 24 bara at -25°C to -20°C	1032 – 1057 kg/m^3
Specific gravity	1.53
Solubility in water	0.148 g/100 g
Flammable	No

1.3.1 Physical Properties

CO_2 is a colourless and odourless gas at normal temperature and pressure (NTP) conditions of 20°C and 1 atm. CO_2 gas is heavier than air, with a specific gravity of 1.53 (air = 1). Therefore, it tends to accumulate at ground level when released into the environment. Due to its odourless properties, it is hard to detect CO_2 during leak scenarios. The occupational exposure limit for CO_2 is around 5,000 parts per million (ppm) over an eight-hour work shift.

CO_2 becomes a solid at temperatures below -78.5°C at atmospheric pressure through deposition and is referred to as dry ice.

Liquid CO_2 cannot occur under atmospheric pressure and only exists at pressures above 5.18 bara, below the critical point temperature of 31.1°C and above the triple point temperature of -56.8°C.

For the four concepts presented in chapter 3, liquid CO_2 should be handled and transported between -20.0°C and -54.3°C depending on the mode of transportation and preferred pressure conditions.

Handling and transporting liquid CO_2 presents several challenges due to its unique physical properties. Maintaining the required low temperatures between -20.0°C and -54.3°C necessitates the use of specialised, thermally insulated equipment to prevent phase changes, where liquid CO_2 can change from liquid to gas or solid. Phase change can lead to catastrophic events during offloading which include over-pressurisation of piping systems during liquid to gas or liquid to solid. The materials of construction for storage, transport vessels and piping systems must be able to withstand these extreme temperatures and pressures.

In addition, where liquid CO_2 is stored under high pressure, any breach in the containment system can lead to a high-pressure release, creating a jet of cold liquid CO_2 that can cause cold burns if it comes into contact with exposed skin and potentially propelling fragments of the containment system.

Furthermore, as CO_2 is heavier than air and odourless, it can accumulate at ground level, posing a risk to safety. CO_2 is not flammable, but it poses significant risks due to its asphyxiating properties. Concentrations of CO_2 above 5% vol/vol in air can be harmful to humans, and concentrations above 12% can be immediately dangerous to life and health. This calls for the use of specific detection systems and regular monitoring to ensure occupational exposure limits are not exceeded. Additionally, the risk of CO_2 freezing requires careful consideration in the design and operation of equipment to prevent blockages and potential damage, as well as ensuring personnel who are carrying out offloading operations use appropriate personal protective equipment (PPE).

Lastly, the environmental impact of CO_2, a potent greenhouse gas, necessitates robust measures to prevent leaks and mitigate their effects, reinforcing the need for high-integrity materials and designs in all aspects of LCO_2 operations.

1.3.1.1 Density

The density of CO_2 is an important factor in the determination of the containment volume required for the storage capacity onboard the ship. A small variation in the pressure and/or temperature can cause significant change in the density of CO_2.

Table 1.2 describes the variation of CO_2 density with changes in temperature and/or pressure taking the transport properties (15.0 barg, -30 °C) in the Northern Lights Project as reference [3].

Table 1.2 – Change in storage volume as the consequence of increasing CO_2 storage pressure [4]

CO_2 pressure [barg]	CO_2 temperature [°C]	CO_2 density [kg/m^3]	CO_2 phase	Required CO_2 storage volume [m^3]
1	15	1.84	Gas	Increase by 99.8%
50	25	131	Gas	Increase by 87.8%
73	33	264	Gas	Increase by 75.5%
73	30	535	Liquid	Increase by 50.3%
50	14	827	Liquid	Increase by 23.1%
7	-50	1152	Liquid	Reduction by 7.1%
15	-30	1076	Liquid	Reference case

barg – Gauge pressure in bar

The low density of CO_2 in the gaseous phase at atmospheric pressure precludes it as an option for onboard storage due to the large containment volumes that would be required (approximately twice the reference case). Although the gas can be compressed to increase its density, the containment volumes required still place the option at infeasible levels.

The density of solid CO_2 is approximately 1500 kg/m^3, and although it provides the best containment volume benefit, it is deemed infeasible mainly due to low temperatures involved, and complex loading and unloading procedures.

Liquefaction of CO_2 into liquid CO_2 provides the optimal balance in the fluid density towards the storage, handling and offloading of captured CO_2 onboard ships.

CO_2 can be liquefied at various pressures and temperatures between the triple point (5.18 bara, -56.6 °C) and the critical point (73.8 bara, 31.1 °C).

When the temperature and pressure conditions approach the triple point, the risk of solidification and dry ice formation can increase especially during transport and offloading of liquid CO_2.

To put the changes in liquid CO_2 density into perspective, Table 1.3 illustrates the density of liquid CO_2 at pressures and temperatures between the triple point and critical point.

Table 1.3 – LCO_2 density relative to pressure and temperature [5]

Pressure	Temperature (°C)	Density (kg/m^3)	
5.18 bara	**-56.6**	1176	(Triple Point)
6 barg	-53.5	1167	
7 barg	-50.0	1152	
8 barg	-47.0	1143	
9 barg	-43.0	1128	
10 barg	-41.0	1120	
15 barg	-30.0	1076	
73.8 bara	**31.1**	**468**	(Critical Point)

Note: bara = barg + atmospheric pressure

1.3.2 Chemical Properties

One carbon dioxide molecule comprises 1 carbon atom and 2 oxygen atoms, with the chemical formula CO_2 and a molecular weight of 44.01 g/mol. Liquid CO_2 is essentially CO_2 (>99% purity) without any impurities. CO_2 dissolved in water forms an acidic solution. It is moderately soluble in water, with an equilibrium solubility of about 1.45 g/L at 25°C due to the polar nature of the carbon dioxide molecule.

CO_2 does not react with or corrode most common materials. However, when dissolved in water, carbonic acid is formed which is corrosive. CO_2 does not exhibit stability or biofouling issues during storage as it is a stable compound and toxic to most living organisms. CO_2 is a greenhouse gas, and operational leakages that occur during production, processing and transportation can contribute to a rise in GHG emissions.

One of the key criteria for the design of LCO_2 storage, handling and offload systems is to minimise operational leakages, which can significantly contribute to climate change. Implementing advanced leak detection systems and regular maintenance schedules, as well as specifying appropriate manifold and interfaces between offloading equipment can help minimise these leaks.

Handling and transporting CO_2 necessitates careful consideration of its chemical properties and potential environmental impacts. For instance, in order to manage a potential corrosive environment through the formation of carbonic acid, materials such as stainless steel or other corrosion-resistant alloys should be used in the construction of storage and transport equipment.

The solubility of water in CO_2, which increases with pressure and temperature, could lead to unexpected dissolution under certain operational conditions. Effective process control and robust dehydration measures in the capture process may be implemented to manage water content and mitigate this risk. To further ensure safety and efficiency, pressure and temperature monitoring systems can be installed. These systems work in tandem with the process control and dehydration facilities to maintain optimal conditions and prevent CO_2 dissolution.

Given the toxicity of CO_2 to most living organisms, stringent safety measures such as regular leak detection tests, emergency response training, and the use of PPE are crucial.

Maintaining high purity of liquid CO_2 (>99%) requires rigorous quality control measures, such as regular sampling and analysis. The stability of liquid CO_2 necessitates continuous monitoring of storage conditions to prevent unexpected reactions or issues. For example, temperature and pressure control systems can be used to maintain the CO_2 in its liquid state and prevent phase changes that could lead to equipment failure or safety risks.

1.3.3 Thermodynamic Properties

Liquid CO_2 is transported and transferred as a pressurised liquid at MP conditions (at pressure of 14.0 to 19.0 bara at -30.5°C to -21.2°C) or LP conditions (at pressure of 5.7 to 10 bara at -54.3°C to -40.1°C). The storage conditions for liquid CO_2 at LP or MP conditions results in multiple offloading configurations. Therefore, understanding its thermodynamic properties is crucial when developing a LCO_2 offloading guideline. The pressure-temperature chart for CO_2, Figure 1.1, illustrates the phases at which CO_2 exists at various temperatures and pressures.

The process of evaporation occurs as heat is added, moving horizontally from the sublimation point through the triple point to the critical point. When heat is added at constant pressure, a phase change occurs, and the resulting evaporated gas is known as "Boil-off Gas" (BOG). Phase change can also occur if the pressure is reduced without adding heat, leading to the instantaneous evaporation of a portion of the mass flow, known as flash gas.

Additionally, if the pressure is reduced below its triple point, a phase change from the liquid to gaseous state will occur. If both pressure and temperature are reduced below triple point to a condition above the solid gas curve, the liquid phase will change to solid phase and dry ice will form.

It should be noted that presence of small amounts of impurities can also significantly alter pressure-temperature phase equilibria and two-phase regions. Minimal concentrations of impurities of hydrogen (H_2) and nitrogen (N_2) can increase vapour pressure making storage and offloading unfeasible due to elevated bubble-point pressures at low temperatures. A summary of the effects of impurities on vapour pressure is summarised in Table 1.4.

Table 1.4 – Effects of impurities on equilibrium pressure of CO_2 mixtures at -50°C [7]

Mixture	Vapour pressure (bara)
100% CO_2	6.7 bara
CO_2 mixture – 0.05 mol% N_2	7.0 bara
CO_2 mixture – 0.1 mol% N_2	7.3 bara
CO_2 mixture – 0.5 mol% N_2	9.7 bara
CO_2 mixture – 0.05 mol% O_2	6.9 bara
CO_2 mixture – 0.05 mol% H_2	10.3 bara
CO_2 mixture – 0.05 mol% CO	7.0 bara
CO_2 mixture – 0.05 mol% Ar	6.8 bara

Note: N_2 – Nitrogen, O_2 – Oxygen, H_2 – Hydrogen, CO – Carbon Monoxide, Ar – Argon

1.4 Hazards Associated with CO_2

1.4.1 Classification of CO_2

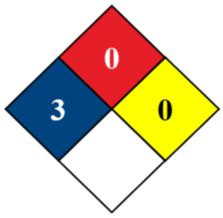
CO_2 is classified as Class 2 (Gases) and Division 2.2 (non-flammable, non-toxic gases) based on the UN Recommendations on the Transport of Dangerous Goods. It is assigned a UN code of 2187. Based on Regulation (EC) No.1272/2008 on Classification, Labelling and Packaging of Substances and Mixtures (CLP Regulations), CO_2 is aligned with existing European Union (EU) legislation to the United Nations Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

The hazard ratings for CO_2 provided by National Fire Protection Association (NFPA) are shown in Table 1.5. The flammability rating is 0 indicating it not being a fire hazard, the instability rating is 0 indicating it being stable and a special rating indicating it being a simple asphyxiant. However, the health hazard rating of 3 underscores the need for safety measures such as the use of PPE, regular safety training, and emergency response plans.

As CO_2 is a simple asphyxiant, adequate ventilation and monitoring systems are essential, especially in enclosed spaces, to prevent oxygen displacement and potential suffocation risks.

Despite CO_2's fire hazard rating of 0, LCO_2 should still be handled with caution. In the event of an external fire adjacent to LCO_2 storage, its rapid expansion and oxygen displacement can create dangerous conditions, necessitating the inclusion of LCO_2 considerations in fire safety plans.

Table 1.5 – Hazard rating of CO_2 [6]

NFPA Rating		
		
Health	3	Can cause serious/permanent injury
Flammability	0	Not flammable
Instability	0	Normally stable, even under fire conditions
Special	Simple asphyxiant	CO_2 is regarded as a simple asphyxiant which becomes hazardous at high concentrations.

1.4.2 Asphyxia

CO_2 has been recognised as a significant workplace hazard primarily due to its ability in displacing oxygen in air posing a threat to life through asphyxiation, and this effect can be profound in low lying areas and confined spaces. The air quality corresponding to the levels of CO_2 in the air is given in Table 1.6.

Table 1.6 – Air quality indication corresponding to levels of CO_2 in the air [8]

CO_2 level in air	Air quality indication
419 ppm	Average atmospheric CO_2 concentration in July 2023 [9]
419–1,000 ppm	Typical level found in occupied spaces with good air exchange
1,000–2,000 ppm	Level associated with complaints of drowsiness and poor air
2,000–5,000 ppm	Level associated with headaches, sleepiness, and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.
5,000 ppm	Permissible exposure limit for daily workplace exposures. At these level, unusual air conditions where high levels of other gases could also be present. Toxicity or oxygen deprivation could also occur.
40,000 ppm	Levels are immediately harmful due to oxygen deprivation.

1.4.3 Toxicity

CO_2 is a normal component of blood gases in humans at low concentration, however higher exposure levels is harmful and can even prove lethal.

Although CO_2 is not classified as acutely toxic under the GHS [10], the level of toxicity is predicated by the concentration and the exposure time to CO_2. The inhalation of elevated concentrations of CO_2 can increase the acidity of the blood triggering adverse effects on the respiratory, cardiovascular, and central nervous systems.

Humans exposed to CO_2 concentration of 3% in air for one hour may experience toxicological symptoms of headaches, while CO_2 concentrations of 17% in air for one minute may experience toxicological symptoms of increased respiratory and heart rate, dizziness, muscle twitching, confusion, unconsciousness, coma and even death. At human exposure to CO_2 concentrations of 50% in air, death is a certainty with the cause being either asphyxiation or the toxicological effect of CO_2 (See Table 1.7).

Table 1.7 – Physiological tolerance time for various carbon dioxide concentrations [11]

CO_2 concentration (%)	Time	Effects
17 – 30	Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death
>10 – 15	1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
7 – 10	Few minutes	Unconsciousness, near unconsciousness
	1.5 minutes to 1 hour	Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
6	1 – 2 minutes	Hearing and visual disturbances
	≤ 16 minutes	Headache, dyspnoea
	Several hours	Tremors
4 – 5	Within a few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnoea
3	1 hour	Mild headache, sweating, and dyspnoea at rest
2	Several hours	Headache, dyspnoea upon mild exertion

The Health, Safety and Environment (HSE) assesses the toxicity of substances through its dangerous toxic load (DTL) assessment to calculate the exposure conditions in terms of concentration and duration of exposure, and these are:

- Specified level of toxicity (SLOT) is defined as causing severe distress to almost everyone in the area; substantial fraction of exposed population requiring medical attention; some people seriously injured, requiring prolonged treatment; highly susceptible people possibly being killed, likely to cause 1-5% lethality rate from a single exposure to a certain concentration over a known amount of time.

- Significant likelihood of death (SLOD) is defined as causing 50% lethality from a single exposure over a known amount of time.

The output of the dangerous toxic load assessment for CO_2 caried out by HSE is shown in the Table 1.8 and the following interpretations made be made from the results.

- A significant danger to humans at CO_2 concentrations above around 7% in air (> 70,000 ppm).
- The effect of that toxicity increasing rapidly for only small changes in concentration above a certain level.

Table 1.8 – Concentration vs time consequences for CO_2 inhalation [12]

Inhalation Exposure Time (mins)	SLOT: 1-5% Fatalities		SLOD: 50% Fatalities	
	CO_2 Concentration in air		CO_2 Concentration in air	
	%	ppm	%	ppm
60	6.3	63,000	8.4	84,000
30	6.9	69,000	9.2	92,000
20	7.2	72,000	9.6	96,000
10	7.9	79,000	10.5	105,000
5	8.6	86,000	11.5	115,000
1	10.5	105,000	14	140,000

The IGC Code chapter 19 classifies CO_2 as an asphyxiant but does not categorise it as toxic although some countries categorise it as toxic providing exposure thresholds in threshold limit value (TLV) and short term exposure limits (STEL) as described in Table 1.9.

In the review of the IGC Code, a proposal to amend the classification for "Carbon dioxide (high purity)" and "Carbon dioxide (reclaimed quality)" to include toxic in addition to asphyxiant has been made to the IMO Sub-Committee on Carriage of Cargoes and Containers. While the IGC code does not set out the specifications for these distinctions in grades, the reclaimed grade is understood to be that which has been captured from industrial processes.

Table 1.9 – CO_2 toxicity thresholds

Source	TLV (ppm)	STEL (ppm)
HSE – Health and Safety Executive (UK)	5,000	15,000 @15 min
OSHA – Occupational Safety and Health Administration (USA)	5,000	-
Cal/OSHA – California OSHA (USA)	5,000	30,000
NIOSH – National Institute for Occupational Health (USA)	5,000	30,000
American Conference of Governmental Industrial Hygienists (USA)	5,000	30,000

Note: UK – United Kingdom, USA – United States of America

1.4.4 Boiling Liquid Expanding Vapour Explosions (BLEVE)

BLEVE is a term used to describe an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure [13], and although it has a low occurrence probability with CO_2 containment systems, the consequences of BLEVE are catastrophic.

It may cause blast waves, dangerous flying fragments, asphyxiation, and intoxication at high concentrations. The occurrence can cause heavy material damage and injury/fatality to personnel onboard and depends on operating condition of the system, the arrangement of the surroundings, weather conditions, and other factors.

1.4.5 Low Temperature

Low temperatures can cause frostbite with direct contact, while embrittlement of steel can cause structural failure of systems that can lead to injury to personnel.

1.4.6 Impurities in CO_2 Stream

The impurities that result in the CO_2 stream may be determined by the type of onboard carbon capture process employed. When CO_2 capture is performed through chemical absorption using an aqueous solution, CO_2 is selectively absorbed by chemical reaction and dissolves very little of other gases such as N_2, H_2 and CO [14]. In contrast, physical adsorption is impacted by the partial pressures of the gas components where N_2, H_2 and other components may be adsorbed along with CO_2 depending on the partial pressures and affinity to the adsorbent. [14]

Impurities are present in CO_2 streams as it is usually more cost effective to leave these impurities in the stream than to remove them at the capture sites. However, even minor concentrations of impurities can decrease the efficiencies of compression, transport and storage stages and raise the risk of safe operation of CO_2 transport pipelines. [15]

The presence of impurities affects the materials of construction for equipment, pipelines, and associated fittings as well as the motive power required for the compression of the CO_2 for storage and transportation. [14]

When CO_2 is utilised as a product, its quality specifications are dictated by the end use, and the “pure” grades used in the food, beverage and specialised industrial typically are required to have a purity of 99.5 to 99.9% [16]. Where grades have the same value for CO_2 purity, the composition profiles may differ as trace impurities may strongly affect the taste or smell.

When the end use is CO_2 sequestration, then the quality specifications of offloaded LCO_2 will be largely defined by the transport pipeline and injection well requirements, [14] and may also need to take into consideration intermediate buffer tanks, if any.

The successful downstream integration of the captured CO_2 in the CCUS value chain hinges on the ability to produce, store and offload industry acceptable CO_2 composition, generally leading to a minimum CO_2 purity level ranging between 93.5% to 96.0%. [16]

Exhaust gas stream from marine diesel engines utilising fossil fuels typically comprise Nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), carbon monoxide (CO), sulphur oxides (SOx), nitrogen oxides (NOx), hydrocarbons, water vapour and smoke.

The quality specifications of captured CO_2 in terms of its absolute purity level and allowable elemental composition of contaminants is yet to be determined. However, indication of the expectations can be largely inferred from the CO_2 value chain involving CO_2 transport in bulk by modular systems and transportation through pipelines, and from studies carried out that provide CO_2 quality recommendations for transport by ships [17] based on the DYNAMIS Project [18].

Table 1.10 illustrates the expectations towards the maximum allowable concentration of contaminants in the CO_2 acceptable to the Northern Lights infrastructure and the recommendations put out in the studies [17] based on the DYNAMIS Project.

Table 1.10 – CO_2 quality recommendations for ship transport (adapted) [19]

Component	Northern Lights specification (ppm)	Recommended in studies by A. Aspelund [20]	Limitation	Reason for limitation
Water (H_2O)	≤ 30	50 ppm	Design and operational considerations	Freeze-out in heat exchangers
Oxygen (O_2)	≤ 10	-	Design and operational considerations	Challenges in the reservoir
Sulphur Oxides (SOx)	≤ 10	-	Health and safety considerations	-
Nitrous Oxides (NOx)	≤ 10	-	Health and safety considerations	-
Hydrogen Sulphite (H_2S)	≤ 9	200 ppm	Health and safety considerations	Short-term exposure limit
Carbon Monoxide (CO)	≤ 100	2000 ppm	Health and safety considerations	Short-term exposure limit
Methane (CH_4)	-	0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Amine	≤ 10	-	Design and operational considerations	-
Ammonia (NH_3)	≤ 10	-	-	-
Hydrogen (H_2)	≤ 50	0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Nitrogen (N_2)	-	0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction
Argon (Ar)	-	0.3% v (all non-condensable gases)	Design and operational considerations	Dry ice formation, costs of liquefaction

Component	Northern Lights specification (ppm)	Recommended in studies by A. Aspelund [20]	Limitation	Reason for limitation
Formaldehyde	≤ 20	-	-	-
Acetaldehyde	≤ 20	-	-	-
Mercury (Hg)	≤ 0.03	-	-	-
Cadmium (Cd) Thallium (Tl)	≤ 0.03 (sum)	-	-	-

It is likely that not a single specification will match every project, and these are most often defined on a project-by-project basis. An acceptable compositional range should be determined and documented based on project-specific studies. Risks associated with each contaminant throughout the carbon capture chain could be included, especially if the specification is not met.

Table 1.11 lists the effects of specific impurities if present in the captured CO_2 stream on the downstream systems and processes.

Table 1.11 – Effect of impurities in CO_2 stream

Impurity	Effect
Nitrogen (N_2)	Increases the saturation pressure of liquid CO_2
Nitrous Oxides (NOx)	Enhances corrosion hazards
Oxygen (O_2)	Increases the saturation pressure of liquid CO_2 and enhances corrosion hazards
Sulphur Dioxide (SO_2)	Increases the toxicity risk of the CO_2 stream, reduces the bubble pressure and enhances corrosion hazards
Hydrogen Sulphite (H_2S)	Increases the toxicity risk of the CO_2 stream and risk of metal embrittlement
Water vapour	Enhances the risk of corrosion and risk of hydrate formation

1.4.7 Phase Equilibria

The captured CO_2 upon liquefaction will need to be stored and offloaded in the liquid phase. The presence of relatively small amounts of impurities can significantly alter pressure–temperature phase equilibria and two-phase regions at conditions relevant to CO_2 transportation [21].

There are two inter-related issues in regard to maintaining the phase equilibrium in the CO_2 stream [14]:

- The minimum CO_2 purity required to maintain a single-phase flow, and
- The allowable concentration of specific impurities.

Figure 1.2 shows the comparison of Vapor-Liquid Equilibria for four different binary mixtures of CO_2 with 2 mol% of different impurities (H_2, N_2, Ar and SO_2).

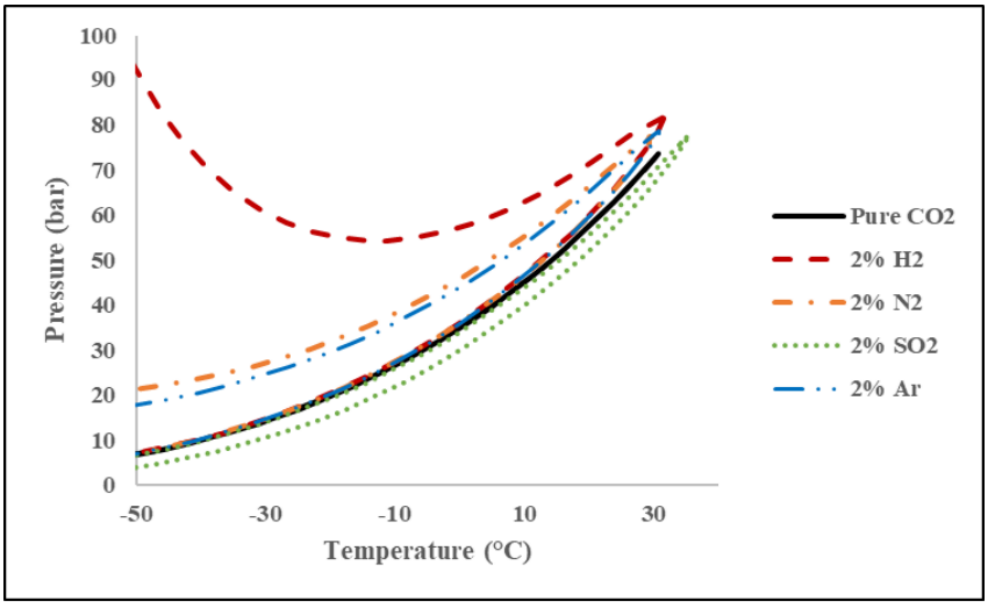


Figure 1.2 – Comparison of phase diagrams for four CO_2 binary mixtures [15]

It can be noted that a mixture with high H_2 concentration leads to a reduced operating window of the transportation pipeline in the liquid phase. Hence, hydrogen plays an important role in determining the required operating pressures to avoid two-phase flow in the pipeline [15].

1.4.8 Solubility of Water

The presence of free water in the CO_2 stream can bring about challenges such as hydrate formation and corrosion of the containment and transfer arrangements, both onboard and ashore.

It can be seen in Figure 1.3 that solubility of water in CO_2 tends to increase with pressure and, more strongly with higher temperatures. The solubility of pure water in low-temperature liquid carbon dioxide decreases from 1000 ppm at 283 K to 180 ppm at 233 K. Liquid CO_2 exhibits higher water-carrying capacity than gas-phase CO_2, therefore water solubility in CO_2 increases significantly during the transition from gaseous to liquid state [21]. Hence, solubility in LCO_2 downstream of liquefaction process need to be considered for suitable technical specification of storage tanks and offloading arrangements.

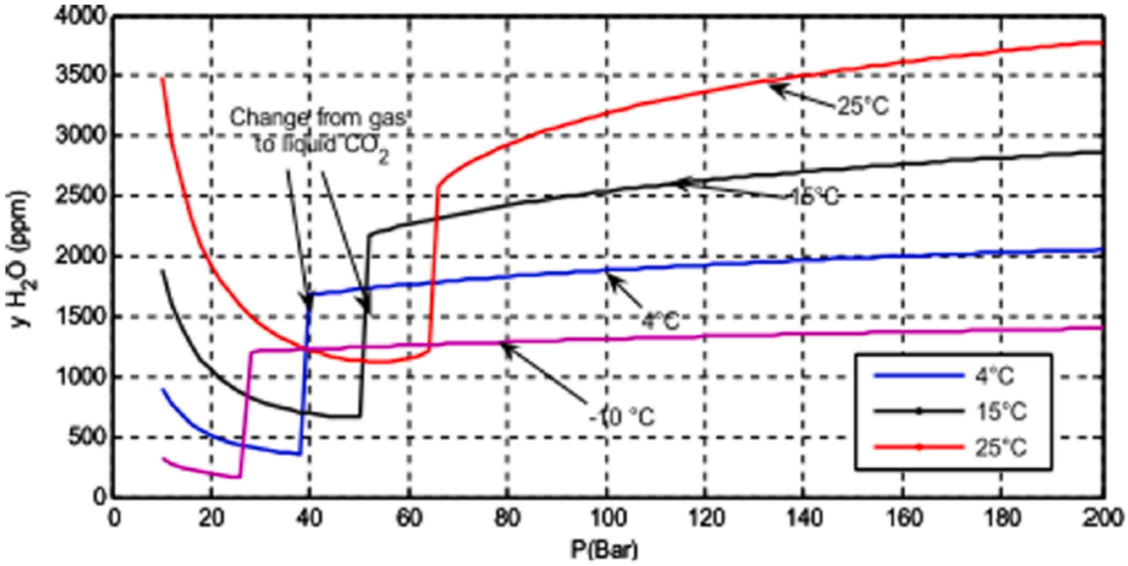


Figure 1.3 – Solubility of water in pure CO_2 [21]

Dehydration process is expected to be included in the processing of the captured CO_2 to reduce the potential for corrosion, hydrate formation and freezing. Otherwise, the cold nature of LCO_2 may cause freezing of any humidity or moisture present in tanks, pipes or equipment which could cause blockages due to the formation of ice, safety valves, pressure gauges, instrument lines or stop valves etc. from operating correctly.

1.4.9 Triple Point

The triple point for CO_2 is where the three phases of gas, liquid and solid of a substance coexist in thermodynamic equilibrium, and these conditions occur at a pressure of 5.18 bara and temperature of - 56.6 °C.

When the temperature and pressure conditions approach the triple point, the risk of solidification and dry ice formation can increase especially during transportation and offloading of LCO_2.

1.5 Onboard Carbon Capture

Onboard carbon capture refers to a process of separation of the CO_2 gas stream and its storage onboard for subsequent discharge onshore, as illustrated in Figure 1.4 below.

Figure 1.4 – Onboard carbon capture and storage process flow

A review of literature reveals that CCS is a mature process in several sectors onshore. CO_2 capture is an integral part of several industrial processes and, accordingly, technologies to separate or capture CO_2 from flue gas streams have been commercially available for many decades.

In practice, the most appropriate capture technology for a given application depends on a number of factors, including the initial and final desired CO_2 concentration, operating pressure and temperature, composition and flow rate of the gas stream, integration with the original facility, and cost considerations. [22]

Regarding maritime industry, the OCCS concept has gathered momentum recently with carbon capture onboard ships deemed as an important pathway in meeting the IMO goals.

The CO_2 captured through the onboard carbon capture system needs to be stored on the ship for eventual discharge ashore ensuring that the storage containment is suitable for:

- Capability to maintain the required phase – solid, liquid or gas, and
- Capacity commensurate with the time between offloading.

The offloading arrangements onboard the ships will need to be compatible with the onshore reception infrastructure in terms of the phase in which the stored CO_2 will be offloaded and interfacing offloading arrangements.

1.5.1 CO_2 Capture

The CO_2 capture onboard ships could be achieved by either by:

1. Pre-combustion capture,
2. Oxy-fuel combustion,
3. Post-combustion capture.

- Pre-combustion capture – This involves separating the carbon from hydrogen using a series of chemical reactions, and the hydrogen utilised as fuel while the separated carbon stored onboard for disposal.
- Oxy-fuel combustion – This involves combustion of the fuel in an oxygen rich environment which results CO_2 rich exhaust gas comprising primarily CO_2 and water.
- Post-combustion capture – This involves capturing the ship's exhaust gas by one of the several methods listed below.
  - Chemical absorption wherein the CO_2 from the exhaust gas is separated by absorption by a chemical solvent and is then recovered from the solvent by a regeneration process onboard. There are some onboard carbon capture systems installed on ships where the saturated chemical solvent is offloaded and the CO_2 is recovered from the solvent ashore.
  - Membrane separation wherein the CO_2 from the exhaust gas is separated through selective permeation through a physical membrane.
  - Cryogenic separation involves cooling the exhaust gas to very low temperatures, which causes the CO_2 to condense into a liquid that can be stored.
  - Physical separation wherein CO_2 is captured by adsorption on solid materials that have the ability to adsorb CO_2 molecules from the exhaust gas.

The most advanced and widely adopted capture technologies are chemical absorption and physical separation.

1.5.2 CO_2 Processing

The captured CO_2 needs to be processed to attain the characteristics and quality requirements acceptable to the containment and offloading arrangements onboard the ship as well as those of transportation and storage onshore and the end use of the offloaded product.

Broadly, the captured CO_2 will need to meet two specifications: -

- A product specification which is dictated by its end use of the offloaded CO_2, whether for utilisation or geological sequestration.[16]
- A requirement specification which would be related to the handling of the captured CO_2 during storage onboard and transportation onshore (pipelines or modular), so that CO_2 can be stored and handled safely, effectively and without causing any damage (corrosion, etc) to the system. [16]

Basis this, the captured CO_2 will need to go through appropriate processing to achieve the required conditions for storage on ships, offloading from ships and transportation onshore for utilisation, intermediate storage or geological sequestration.

Depending on the desired conditions of storage and eventual offloading from ships, the processing of the captured CO_2 could involve compression, dehydration and liquefaction processes. The CO_2 phase and specifications will dictate the conceptualisation of the design of the onboard carbon capture system, and the main components may include compressors, heat exchangers, driers, storage tanks, reliquefaction plants and discharge pumps.

1.5.3 CO_2 Phase Selection

Depending on the onboard capture process employed, the captured CO_2 could be in either gaseous or liquid phases.

With the chemical absorption method expecting to be the optimal process for onboard CO_2 capture, the retention of the captured CO_2 in gaseous phase or it being processed to solid CO_2 or liquid CO_2 will be a decision dictated by factors including density, containment volume, phase handling characteristics, process equipment and process energy intensity.

1.6 References

[1] C. Spitzenberger, "Carbon Dioxide Major Accident Hazard Awareness," 2023.

[2] The Engineering ToolBox. Carbon Dioxide – Thermophysical Properties. January 2024 [Online]. Available: https://www.engineeringtoolbox.com/CO2-carbon-dioxide-properties-d_2017.html

[3] Equinor, "Northern Lights Feed Report," 2020.

[4] M. Michel, "GHGT-16 Ship-based CO_2 capture – Port integration".

[5] E. P.J. Linstrom and W.G. Mallard, "NIST Chemistry WebBook, NIST Standard Reference Database Number 69," National Institute of Standards and Technology, Gaithersburg MD, 20899, https://doi.org/10.18434/T4D303, [Online]. Available: https://webbook.nist.gov/chemistry/fluid/. [Accessed 3 January 2024]

[6] "CO_2 Meter," 2017. [Online]. Available: https://www.co2meter.com/en-uk/blogs/news/nfpa-704-sign-for-co2#:~:text=For%20stored%20carbon%20dioxide%20gas. [Accessed 14 July 2023].

[7] T. Vermeulen, "Knowledge sharing report – CO_2 Liquid Logistics Shipping Concept (LLSC): Overall Supply Chain Optimization," 2011.

[8] Breeze Technologies, "Everything to know about carbon dioxide (CO_2)," 2015.

[9] CO_2Earth, "Daily CO_2," 2023.

[10] United Nations, " Globally Harmonised System of Classification and Labelling of Chemicals (GHS)".

[11] U.S. Environmental Protection Agency, Carbon Dioxide as a Fire Suppressant: Examining the Risks, February 2000 [Online] (Carbon Dioxide as a Fire Suppressant: Examining the Risks (EPA, 2000) | US EPA) Appendix B - Overview of Acute Health Effects, May 2023.[Online]. Available : https ://www.epa.gov/sites/default/files/2015-06/documents/co2appendixb.pdf.

[12] W. J. B. M. Harper P, "HSE Assessment of the major hazard potential of carbon dioxide (CO_2)," HSE, 2015.

[13] J. Venart, "BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS (BLEVE); possible failure mechanisms and their consequences," IchemE, 2000.

[14] BSI, " ISO/TR 27912 – Carbon dioxide capture — Carbon dioxide capture systems, technologies and processes".

[15] Luna-Ortiz, et al, "Impact of Hydrogen as Impurity in the Physical and Transport Properties of CO_2 Streams in CCS/CCUS Transport Systems: A Technical Discussion," 2021.

[16] P. A. Brownsort, "EU CCUS Project Network – Briefing on carbon dioxide specifications for transport," 2019.

[17] A. Aspelund, Gas purification, compression and liquefaction processes and technology for carbon dioxide (CO_2) transport, 2010.

[18] E. d. V. a. C. Hendriks, Towards Hydrogen and Electricity Production with Carbon Dioxide Capture and Storage, 2007.

[19] A. Reyes-Lúa, 4th Report of the Thematic Working Group on: CO_2 Transport, Storage, and Networks, 2021.

[20] Aspelund A, Mølnvik MJ, De Koeijer G., "Ship Transport of CO_2- Technical Solutions and Analysis of Costs, Energy Utilisation, Exergy Efficiency and CO_2 Emissions. Chem Eng Res Des," 2006.

[21] H. A. Baroudi, "A review of large-scale CO_2 shipping and marine emissions management for CCUS," 2021.

[22] IEA, Net Zero by 2050: A Roadmap for the Global Energy Sector.

[23] A. P. (. K. Richard Doctor (United States), "Chapter 4: Transport of CO_2," in *IPCC Special Report on Carbon dioxide Capture and Storage*, 2005, pp. 179-194.

2. Onboard Storage of Captured CO_2

The efficient and optimised storage of the captured CO_2 onboard a ship for eventual offloading is a crucial part for the installation or retrofitting of OCCS. This is especially the case with existing assets with highly optimised cargo carrying capacities where the space required for the CO_2 storage tanks may come at a certain cost of loss of cargo capacity for existing vessels.

2.1 Storage Conditions

With the understanding that CO_2 can be held in liquid phase between the triple point and the critical point, liquid CO_2 storage conditions are categorised into LP, MP and high pressure (HP) conditions.

The density of CO_2 is an important factor to determine the containment volume required for the storage capacity onboard the ship.

The density of saturated CO_2 liquid will range from about 1176 kg/m^3 at the triple point to about 468 kg/m^3 at the critical point (CP). Thus, for a given containment volume, approximately twice the amount of liquid CO_2 can be stored at conditions closer to the triple point as compared to the conditions near the critical point.

At higher pressure and temperatures, the pressure required for liquefaction increases, requiring thick-walled tanks that can withstand higher pressures, which makes the HP conditions not viable for marine transportation. At lower pressure and temperatures, the pressure required for liquefaction is reduced, allowing the storage and transportation in relatively thin-walled tanks.

The liquefaction and storage of CO_2 under LP or MP conditions have been considered as viable options based on the energy intensity for liquefaction and the weight of the tanks.

A third option for LCO_2 storage onboard ships, in addition to LP and MP conditions, is the use of dedicated vacuum insulated ISO tank container where LCO_2 can be kept in liquid form under a pressure of 18 to 24 bara. These are likely to be 20 ft ISO tank containers with capacity for 19 m^3 of LCO_2. Both 20 ft and 40 ft ISO tank containers are rated to 36,000 kg maximum gross weight. A full 40 ft ISO tank container of LCO_2 exceeds the maximum gross weight. This is also the US road weight limitation. Thus, 40 ft ISO tank container cannot be used for carriage of LCO_2.

The typical categorisation of LCO_2 storage conditions for maritime and their relative advantages / disadvantages are listed in Table 2.1 and Table 2.2 respectively.

Table 2.1 – Typical categorisation for LCO_2 storage conditions

Triple Point	Low Pressure (LP)	Medium Pressure (MP)	ISO Tank Container	Critical Point
5.18 bara	5.7 to 10.0 bara WP: 8.0 bara	14.0 to 19.0 bara WP: 16.0 bara	18.0 to 24.0 bara WP: 22.0 bara	73.8 bara
-56.6 °C	-54.3°C to -40.1°C	-30.5°C to -21.2°C	-25.0 °C to -20.0°C	31.1°C

Table 2.2 – Comparison between LP, MP and ISO tank container conditions of LCO_2 (adapted) [1]

Condition	Advantages	Disadvantages
LP	High density state allows for more CO_2 transported per tank which can optimise space by having smaller tank and/or increase offloading duration. Established know-how from liquefied petroleum gas (LPG) ship handling experience.	Proximity to solid phase. Higher quality material may be required to handle lower temperature. High conditioning costs. Complex insulation of the tanks.
MP	The medium pressure storage option results in less quantity of CO_2 transported per tank. This is a commercially mature concept especially in the food and beverage industries where smaller quantities of CO_2 is required.	Greater wall thickness leading to increase in weight per unit of volume of CO_2 transported in the tank. Storage tanks are likely smaller in size which leads to requiring more tanks to accommodate the same volume as compared to the LP option.
ISO Tank Container	Low conditioning costs. Proven technology. Readily usable with versatility for transportation and distribution of the gas.	Not suitable for storage of large quantities of LCO_2 (maximum storage about 20 m^3 per container). Complex piping and manifold arrangements if intended to make storage rack arrangement for ISO tank container cassettes.

For ships with OCCS, onboard storage of LCO_2 at MP conditions of 14.0 to 19.0 bara at -30.5°C to -21.2°C (WP: 16.0 bara at -30.0°C) ensures safe operation away from triple-point conditions mitigating risk of dry ice formation whilst retaining LCO_2 at high-density. Alternatively, due to Capital Expenditure (CAPEX) considerations, it may also be stored in LP conditions of 5.7 to 10.0 bara at -54.3°C to -40.1°C (WP: 8.00 bara at -50.0°C).

The choice of liquid phase is primarily based on fluid density for storing captured CO_2, with CCUS value chain alignment dictating offloading in liquid phase. The liquefaction and storage of CO_2 under either LP or MP conditions are both viable options considering process energy intensity and storage tank weight to product quantity ratio, except for ISO tank containers, which have specific storage conditions of 18.0 to 24.0 bara (WP: 22.0 bara) at -25.0°C to -20.0°C. Some may favour LP condition due to higher density LCO_2 and lower CAPEX, although finding the optimal balance away from triple point for safe handling during offloading and transportation remains crucial.

2.2 Selection of Materials

The design for the storage tanks, equipment and pipelines should take into account the following aspects in the selection of materials of the onboard carbon capture system.

- Effect of impurities in the CO_2 stream – Presence of water content in the CO_2 stream can lead to corrosion where stainless steel offers the best protection, but carbon steel can be used when low water content is achieved.

- Operational temperature range – The material is required to withstand not only the operational temperature range of the CO_2 stream in liquid phase but the low temperatures that can arise due to rapid depressurisation.

Table 2.3 summarises a typical selection of materials for a CO_2 terminal and provides an insight into the materials that may be utilised in the onboard carbon capture system for its components.

Table 2.3 – Material selection for ships carrying CO_2 (adapted) [2]

Component	Medium	Temperature	Pressure	Material
Storage tanks	LCO_2	-50.0	7.0 barg	5% Ni steel
Pumps	LCO_2	-50.0	7.0 – 45.0 barg	SS316L
Heat exchangers	Tube side: Seawater Shell side: LCO_2	-50.0	45.0 barg	Shell: SS304 Tubes: Titanium

2.3 CO_2 Storage Tanks

The IMO adopted "The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)" for the design of hull and tank structure of liquid gas transport ships such as LPG and Liquefied Natural Gas (LNG) carriers, and with LCO_2 covered under the IGC Code, CO_2 carriers are designed and constructed under this code. [3]

The mature experience in LPG/LNG carriers has been identified to be beneficial in the design of equipment for onshore and offshore offloading of LCO_2.

Table 2.4 describes the typical conditions that are used in the transportation of CO_2 by different modes.

Table 2.4 – Typical conditions and properties across the transportation of CO_2 [4]

Properties	Typical CO_2 buffer storage and transport by ship	Typical CO_2 buffer storage and transport by road	Typical CO_2 transport by pipelines	Typical CO_2 injection and storage (sequestration)
State/Phase	Semi-refrigerated liquid	Semi-refrigerated liquid	Semi-refrigerated fluid (dense phase)	Supercritical fluid (dense phase)
Density	1,163 kg/m^3	1,078 kg/m^3	838 kg/m^3	702 kg/m^3
Density ratio (liquid/gas)	588	545	424	355
Pressure	6.5 barg	20.0 barg	73.0 – 150.0 barg	100.0 barg

Properties	Typical CO_2 buffer storage and transport by ship	Typical CO_2 buffer storage and transport by road	Typical CO_2 transport by pipelines	Typical CO_2 injection and storage (sequestration)
Temperature	-52.0 °C	-30.0 °C	20.0 °C	35.0 °C

In general, there are three types of storage tanks commonly used for the transport of liquid gases [12] and these are listed below:

- **Pressure type** designed to prevent or limit boiling of gas under ambient conditions usually used in small gas carriers.
- **Low-temperature type (Fully refrigerated)** designed to operate at low temperatures to keep gas as a liquid under atmospheric pressure. It is generally suitable for large scale transport such as LPG and LNG carriers.
- **Semi-refrigerated type** combines both the pressure and low temperature type and is pressured and cooled for gas to be kept as liquid.

Table 2.5 lists the types of storage tanks that have been interpreted to be suitable for respective pressure conditions.

Table 2.5 – Pressurised storage tank types found on ships

Source	Type of storage tanks	Size or Capacity	Material grade	Conditions
Decarre et al. [5]	Cylindrical or bi-lobate	14 x 4,500 m^3	3.5%, 5% and 9% Ni Stainless steel 304L and 316L Aluminium 1050	15.0 barg, -30.1 °C
Haugen et al. [6]	Cylindrical	3,000 t	Steel	15.0 barg, 28.1 °C
Aspelund et al. [7]	Semi-pressurised cylindrical tanks	10 x 3,000 m^3	Steel	6.5 barg, -52.1 °C
Vermeulen [2]	Bullet type tanks	3-10 x 10,000 m^3	P335NL2	7.0 barg, -50.1 °C
Seo et al. [8]	Cylindrical	90 – 5,000 m^3	A517 Steel	6.0 barg, -52.1 °C 15.0 barg, -27.1 °C

The LCO_2 storage tank onboard a ship is likely to be an independent tank which is self-supporting and does not form part of the ship's structure. As defined in the IGC Code, and depending primarily on the design pressure there are three different types of independent tanks – Type A, B and C.

Type A Independent Tanks – These are designed using classical ship structural analysis techniques where the tank primarily consists of plane surfaces (gravity tanks). The design vapour pressure should not exceed 0.7 barg, which means cargoes must be carried in a fully refrigerated condition at or near atmospheric pressure.

Type B Independent Tanks – These are independent tanks designed using model tests, refined analytical tools and analysis methods to determine stress levels, fatigue life and crack propagation characteristics. Type B independent tanks can be constructed of flat surfaces, termed 'prismatic' or they may be of the spherical type. Due to the enhanced design factors, Type B tanks require only a partial secondary barrier in the form of a 'drip tray'.

Type C Independent Tanks – The Type C tank, which is also referred to as a pressure vessel, is a tank meeting pressure vessel criteria. Such tanks may be of various shapes, from spherical to cylindrical or bilobe. Cylindrical vessels may be vertically or horizontally mounted.

Considering the previously discussed storage conditions of LCO_2, semi-refrigerated Type C tank or ISO tank container is considered as suitable solution for LCO_2 storage onboard ships with OCCS.

2.4 Capacity of LCO_2 Storage Tanks

2.4.1 Capacity of LCO_2 Tanks for Voyage CO_2 Emission Reductions

The storage of the captured CO_2 will require a considerable containment volume dependent on factors such as ship size, engine output, fuel type used for combustion, ship's trading distance, capture rate, days of operation at sea, and frequency of discharging captured CO_2.

The storage tank volumes for LP and MP conditions were calculated for a representative Panamax container ship, a Panamax bulk carrier and a Long Range 2 (LR2) tanker with actual voyage and fuel consumption data for the respective selected sample vessels as listed in Table 2.6.

Table 2.6 – Ship performance data for year 2021

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Length of vessel (m)	301.0	225.0	239.0
Breadth of vessel (m)	40.0	32.0	42.0
Deadweight (metric tonnes – MT)	83,964.0	74,133.0	1,056,99.0
Twenty equivalent unit (TEU)	6600	NA	NA
Annual distance sailed (Nm)	99,729.0	31,702.0	34,887.0
Total hours sailed	6,380.0	2,783.0	2,987.0
Total days sailed	265.8	115.9	124.5
Average speed (knots)	15.6	11.4	11.7
Annual Heavy Fuel Oil (HFO) (MT)	23,206.0	2,059.0	4,375.0
Annual Light Fuel Oil (LFO) (MT)	95.0	1,230.0	1,128.0
Annual Diesel/Gas Oil (MT)	2,220.0	193.0	112.0

The average daily fuel consumption at sea for each sample vessel is as per Table 2.7.

Table 2.7 – Daily average consumption at sea

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Daily HFO consumption (MT)	87.3	17.8	35.2
Daily LFO consumption (MT)	0.4	10.6	9.1
Daily Diesel/Gas oil consumption (MT)	8.4	1.7	0.9

The average daily CO_2 emissions based on the average fuel consumption of the sample vessels is calculated taking the emission factors of HFO as 3.114 CO_2/MT fuel, LFO as 3.151 CO_2/MT fuel and Diesel/Gas oil as 3.206 CO_2/MT fuel is as per Table 2.8.

Table 2.8 – Calculated daily average CO_2 emissions

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Daily CO_2 emitted from HFO consumption (MT)	271.9	55.4	109.6
Daily CO_2 emitted from LFO consumption (MT)	1.3	33.4	28.7
Daily CO_2 emitted from Diesel oil consumption (MT)	26.9	5.5	2.9
Total daily CO_2 emitted (MT)	300.1	94.3	141.2

CO_2 capture rate of a carbon capture system is defined as the ratio of the captured CO_2 mass flow rate at CO_2 capture system to the inlet CO_2 mass flow rate to CO_2 capture system. OCCS vendors claim their system capture rate to be 30% - 90%. Assuming 70% capture rate of CO_2 by the OCCS, the total CO_2 that will be captured and requiring storage onboard is shown in Table 2.9. A capture rate of 70% has been assumed which is expected to be more commonly found and practical for ships in service as it is a good balance between capital investment and regulatory compliance.

Table 2.9 – CO_2 captured quantity assuming 70% capture rate

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Total daily CO_2 (MT) at 70% capture rate	210.1	66.0	98.9

Captured CO_2 onboard ships is expected to be stored and handled refrigerated in liquid form in either LP or MP condition in insulated storage tanks or ISO tank container type containment systems. ISO tank containers are considered for container ships due to their cellular stowage characteristics. The types of storage tanks being considered suitable for each vessel type are tabulated in Table 2.10.

Table 2.10 – Storage tanks optimal for vessel types

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Storage Tank Type	Type C / ISO Tank Container	Type C	Type C
Storage Tank Condition	LP / MP / ISO Tank Container	LP / MP	LP / MP

The tank design conditions for onboard storage of captured CO_2 in liquid phase as LCO_2 are detailed in Table 2.11.

Table 2.11 – LP, MP and ISO tank container storage conditions

Tank Design Conditions	Pressure	Temperature	Average Density of CO_2 *
LP	5.7 to 10.0 bara	-54.3°C to -40.1°C	1.1435 MT/m^3
MP	14.0 to 19.0 bara	-30.5°C to -21.2°C	1.0575 MT/m^3
ISO Tank Container (20 foot, 20 m^3 net)	18.0 to 24.0 barg	-25.0 °C to -20.0 °C	1.0445 MT/m^3

*Note – Average density is the arithmetic average of max/min density for the tank design condition.

Assuming 70% capture rate values obtained in Table 2.9, the storage capacity required under different pressure conditions is calculated and described in Table 2.12.

Table 2.12 – Storage requirements at LP, MP and ISO tank container conditions

Tank Design Conditions	Panamax Container Ship	Panamax Bulk Carrier	LR2 Tanker
LP (m^3/day)	183.7	57.7	86.4
MP (m^3/day)	198.6	62.4	93.5
ISO Tank Container (m^3/day)	201.1 (10 ISO tank containers)	NA	NA

Panamax Container Ship

The storage tank types and their required capacities for eight to– 20 days voyage have been calculated based on 70% capture rates for the sample Panamax container ship in Table 2.13 and represented in Figure 2.1.

Table 2.13 – Storage capacity requirements for Panamax container ship

Operational days	LP Tank (m^3)	MP Tank (m^3)	ISO Tank Containers (m^3)
CO_2 capture per day @70 % capture rate	183.7	198.6	201.1
8 days	1,469.6	1,588.8	1,608.8
9 days	1,653.3	1,787.4	1,809.9
10 days	1,837.0	1,986.0	2,011.0
11 days	2,020.7	2,184.6	2,212.1
12 days	2,204.4	2,383.2	2,413.2
13 days	2,388.1	2,581.8	2,614.3
14 days	2,571.8	2,780.4	2,815.4
15 days	2,755.5	2,979.0	3,016.5
16 days	2,939.2	3,177.6	3,217.6
17 days	3,122.9	3,376.2	3,418.7
18 days	3,306.6	3,574.8	3,619.8
19 days	3,490.3	3,773.4	3,820.9
20 days	3,674.0	3,972.0	4,022.0

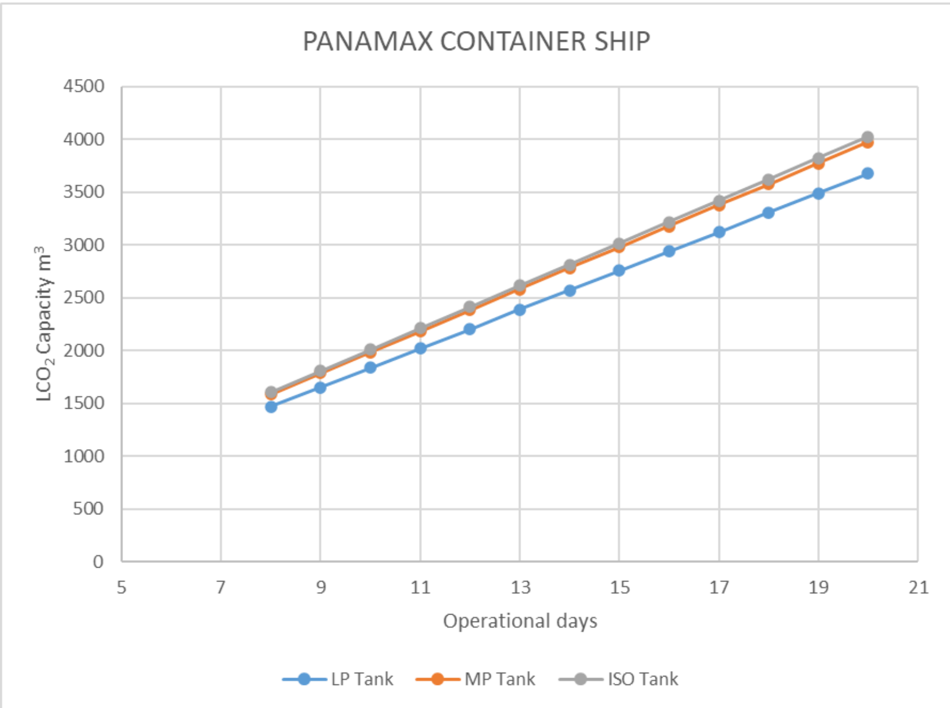


Figure 2.1 – Storage capacity requirements for Panamax container ship

Panamax Bulk Carrier

The storage tank types and their required capacities for eight to– 20 days voyage have been calculated based on 70% capture rates for the sample Panamax bulk carrier in Table 2.14 and represented in Figure 2.2.

Table 2.14 – Storage requirements for Panamax bulk carrier

Operational Days	LP Tank (m^3)	MP Tank (m^3)	ISO Tank Containers (m^3)
CO_2 capture per day @70 % capture rate	57.7	62.4	NA
8 days	461.6	499.2	NA
9 days	519.3	561.6	NA
10 days	577.0	624.0	NA
11 days	634.7	686.4	NA
12 days	692.4	748.8	NA
13 days	750.1	811.2	NA
14 days	807.8	873.6	NA
15 days	865.5	936.0	NA
16 days	923.2	998.4	NA
17 days	980.9	1,060.8	NA
18 days	1,038.6	1,123.2	NA
19 days	1,096.3	1,185.6	NA
20 days	1,154.0	1,248.0	NA

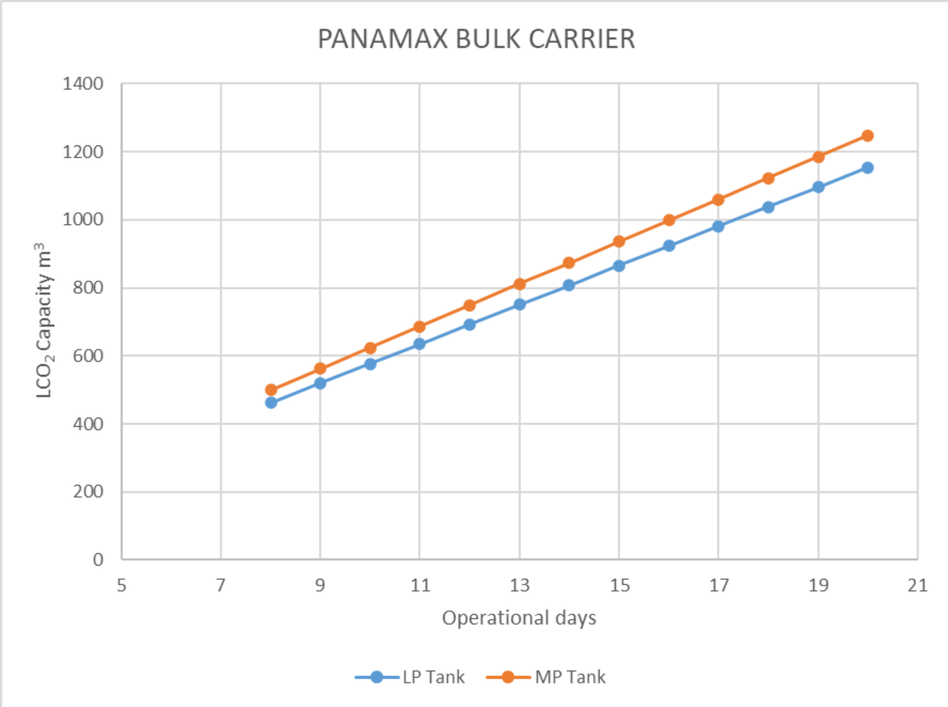


Figure 2.2 – Storage requirements for Panamax bulk carrier

LR2 Tanker

The storage tank types and their required capacities for 8 – 20 days voyage have been calculated based on 70% capture rates for the sample LR2 tanker vessel in Table 2.15 and represented in Figure 2.3.

Table 2.15 – Storage requirements for LR2 tanker

Operational Days	LP Tank (m^3)	MP Tank (m^3)	ISO Tank Containers (m^3)
CO_2 capture per day @70 % capture rate	86.4	93.5	NA
8 days	691.2	748.0	NA
9 days	777.6	841.5	NA
10 days	864.0	935.0	NA
11 days	950.4	1,028.5	NA
12 days	1,036.8	1,122.0	NA
13 days	1,123.2	1,215.5	NA
14 days	1,209.6	1,309.0	NA
15 days	1,296.0	1,402.5	NA
16 days	1,382.4	1,496.0	NA
17 days	1,468.8	1,589.5	NA
18 days	1,555.2	1,683.0	NA
19 days	1,641.6	1,776.5	NA

Operational Days	LP Tank (m^3)	MP Tank (m^3)	ISO Tank Containers (m^3)
20 days	1,728.0	1,870.0	NA

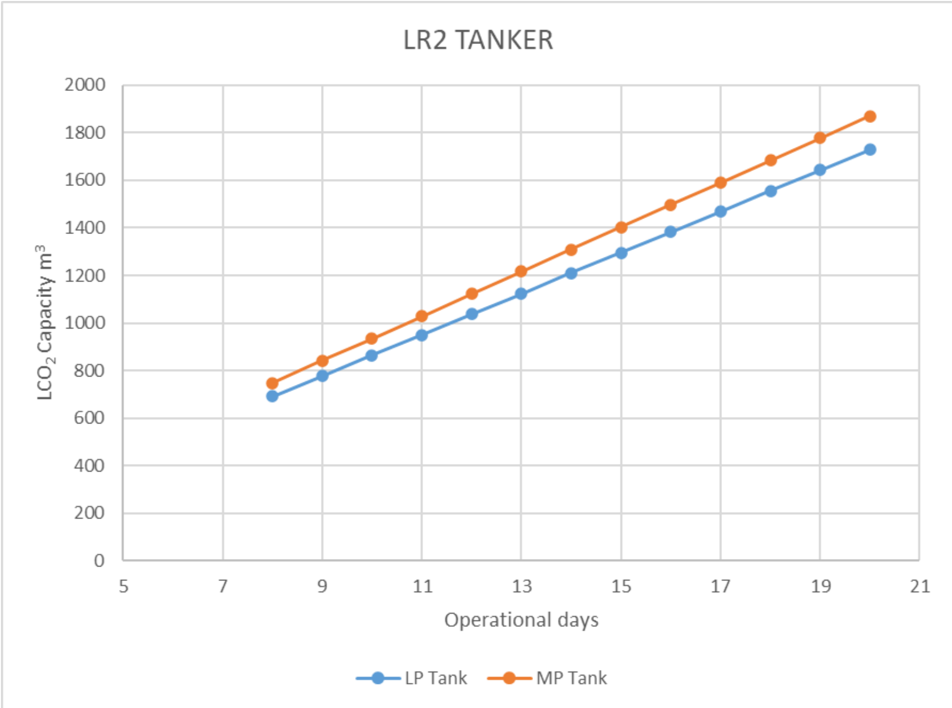


Figure 2.3 – Storage requirements for LR2 tanker

2.4.2 Capacity of LCO_2 Tanks for CII Compliance

The Carbon Intensity Indicator (CII) for ships is a measurement used to assess the environmental impact of a vessel's greenhouse gas emissions, particularly CO_2, relative to its transportation work. It is a metric that helps quantify the amount of CO_2 emissions produced per unit of cargo carried and distance travelled by a ship, or in other words how efficiently a ship can transport goods or passengers.

A vessel's attained CII is represented by the formula:

Attained CII = Annual CO_2 emissions in grams / (Capacity in metric tons x Distance travelled in nautical miles)

For ships where cargo weight is important, the CII takes the form of an Annual Efficiency Ratio (AER) or the emissions per deadweight mile, and for vessels where cargo volume is important, capacity gross ton distance (cgDist) or emissions per gross ton miles is used.

Ships are given an annual CII rating from A to E, A being a vessel with the least CO_2 emissions, while E the most. In order to comply, a vessel should, annually, achieve a CII rating of C and above (B or A), while those vessels with lower ratings, D and E, will need to improve their operational energy efficiency.

Also, in order to ensure reduction in carbon intensity for the global fleet, the IMO includes a reduction factor too which increases over the years making the required CII, harder to achieve. As a result, vessels will need to keep improving the efficiency or risk getting downgraded.

In this section, the storage tank capacity is recalculated based on the vessel's need to achieve CII compliance, with the assumption that carbon capture is accounted in CII calculations. It is assumed that the vessel's performance remains the same through the years so that the attained CII is same for the future years as per the performance data in Table 2.7.

The amount of CO_2 needed to be captured to achieve CII compliance is proportional to the percentage CO_2 emission reduction required to achieve the target CII, assuming no other measures for improving CII are implemented.

Table 2.16, Table 2.17 and Table 2.18 show the Attained Annual CII, Required Annual CII, Target CII, Rating and Percentage efficiency improvement required by the three types of vessels to achieve the minimum CII requirement in 2023, 2024 and 2025.

Table 2.16 – Panamax container ship CII requirement

Panamax Container Ship	2023	2024	2025
Attained CII without any measure implemented	9.516	9.516	9.516
Required Annual CII (gCO_2/t-Nm)	7.368	7.213	7.058
Target CII (gCO_2/t-Nm)	7.327	7.137	7.042
Target CII Rating	C	C	C
Percentage CO_2 emission reduction required to achieve Target CII & Rating	23%	25%	26%

Table 2.17 – Panamax bulk carrier CII requirement

Panamax Bulk Carrier	2023	2024	2025
Attained CII without any measure implemented	4.641	4.641	4.641
Required Annual CII (gCO_2/t-Nm)	4.215	4.126	4.038
Target CII (gCO_2/t-Nm)	4.177	4.084	4.038
Target CII Rating	C	C	C
Percentage CO_2 emission reduction required to achieve Target CII & Rating	10%	12%	13%

Table 2.18 – LR2 tanker CII requirement

LR2 Tanker	2023	2024	2025
Attained CII without any measure implemented	4.756	4.756	4.756
Required Annual CII (gCO_2/t-Nm)	4.295	4.205	4.114
Target CII (gCO_2/t-Nm)	4.280	4.185	4.090
Target CII Rating	C	C	C
Percentage CO_2 emission reduction required to achieve Target CII & Rating	10%	12%	14%

To achieve the required CII rating, the CO_2 emission reduction required should be captured by the OCCS. Besides this, the onboard carbon capture system itself uses energy to separate and capture CO_2 from exhaust gas. It is also needed to capture the additional CO_2 emitted due to energy consumption of the onboard carbon capture system to achieve the required CII. This amount will vary depending on the design of the OCCS and the ship's fuel consumption. Thus, the total amount of CO_2 needed to be captured will be as illustrated in Figure 2.4. Based on available information, the additional CO_2 generated by the OCCS to capture the CO_2 from vessel exhaust is estimated to be around 40%-45%. The higher value of 45% is chosen for our calculations below and is taken into account while cumulatively calculating the effective CO_2 capture needed by the vessel to achieve CII compliance.

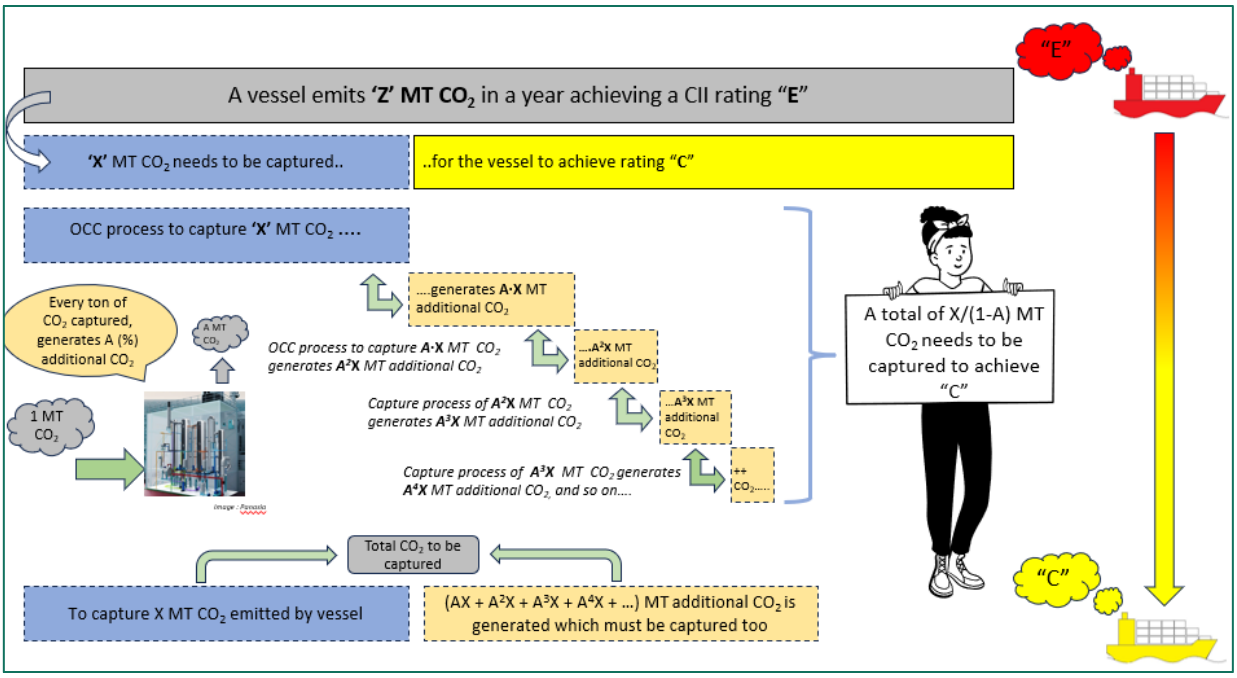


Figure 2.4 – Amount of CO_2 to be captured to achieve CII compliance

Table 2.19 below shows the methodology for calculating the total CO_2 capture required by a Panamax Container ship to achieve CII compliance in 2023.

Table 2.19 – Total CO_2 capture calculation methodology to achieve CII compliance (adapted) [9]

Panamax container ship total CO_2 capture calculation methodology	
Total CO_2 emitted in 2021: 79680 MT	
CO_2 to be captured to achieve CII compliance in 2023 (23% reduction in CO_2 emissions) (MT)	18,326.4
Additional CO_2 generated by CCS system to capture 18326.4 MT CO_2 (MT)	8,246.9
Additional CO_2 generated by CCS system to capture 8246.9 MT CO_2 (MT)	3711.1
Additional CO_2 generated by CCS system to capture 3711.1 MT CO_2 (MT)	1,670.0
Additional CO_2 generated by CCS system to capture 1670 MT CO_2 (MT)	751.5
Additional CO_2 generated by CCS system to capture 751.5 MT CO_2 (MT)	338.2
Additional CO_2 generated by CCS system to capture 338.2 MT CO_2 (MT)	152.2
Additional CO_2 generated by CCS system to capture 152.2 MT CO_2 (MT)	68.5

Panamax container ship total CO_2 capture calculation methodology	
Additional CO_2 generated by CCS system to capture 68.5 MT CO_2 (MT)	30.8
Additional CO_2 generated by CCS system to capture 30.8 MT CO_2 (MT)	13.9
Additional CO_2 generated by CCS system to capture 13.9 MT CO_2 (MT)	6.2
Additional CO_2 generated by CCS system to capture 6.2 MT CO_2 (MT)	2.8
Additional CO_2 generated by CCS system to capture 2.8 MT CO_2 (MT)	1.3
Additional CO_2 generated by CCS system to capture 1.3 MT CO_2 (MT)	0.6
Total cumulative CO_2 to be captured to achieve CII compliance in 2023 (MT)	33,320.32

The methodology in Table 2.20 can be mathematically expressed as follows:

$$\boldsymbol{CO_{2\,(TC)}} = \frac{\boldsymbol{CO_{2\,(IC)}}}{\boldsymbol{1 - a}}$$

where,

$CO_{2(IC)}$ is the amount of CO_2 to be initially captured for CII compliance.

$CO_{2(TC)}$ is the total amount of CO_2 to be captured with OCCS in operation for CII compliance.

'a' is the percentage additional CO_2 generated due to OCCS operation to capture the $CO_{2(IC)}$ from vessel exhaust.

Similarly, using the same methodology, the calculations for the total CO_2 capture required to achieve CII compliance for Panamax container ship, Panamax bulk carrier and LR2 Tanker for years 2023, 2024 and 2025 are listed in Table 2.20.

Table 2.20 – Total annual CO_2 capture requirement for CII compliance

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Total CO_2 emitted in 2021 (MT)	79,680.0	10,906.0	17,537.0
Amount of CO_2 to be captured to achieve CII compliance in 2023, including additional CO_2 generated by OCCS (MT)	33,320.3	1,982.6	3,188.1
Amount of CO_2 to be captured to achieve CII compliance in 2024, including additional CO_2 generated by OCCS (MT)	36,217.7	2,379.2	3,825.7
Amount of CO_2 to be captured to achieve CII compliance in 2025, including additional CO_2 generated by OCCS (MT)	37,666.5	2,577.4	4,463.3

Based on above, the amount of CO_2 to be captured for a 20-day voyage to achieve CII compliance in the year 2023, 2024 and 2025 is listed in Table 2.21.

Table 2.21 – CO_2 capture required for CII compliance for 20-day voyage

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Amount of CO_2 to be captured for a 20-day voyage in 2023, MT	2,506.9	342.0	512.3
Amount of CO_2 to be captured for a 20-day voyage in 2024, MT	2,724.9	410.4	614.8
Amount of CO_2 to be captured for a 20-day voyage in 2025, MT	2,833.8	444.6	717.2

ISO tank container units are considered for storage for the Panamax container vessel while MP containment is considered for Panamax bulk carrier and LR2 tanker. Considering the average density for MP condition as 1.0575 MT/ m^3 and ISO tank container condition as 1.0445 MT/ m^3 the tank capacities required to achieve CII compliance in the year 2023, 2024 and 2025 are listed in Table 2.22.

Table 2.22 – Storage capacity required for CII compliance

Vessel Type	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Selected tank type	ISO tank containers	MP tanks	MP tanks
Tank capacity for CO_2 storage for a 20-day voyage in 2023 (m^3)	2,400.1 (120 ISO tank containers)	323.4	484.5
Tank capacity for CO_2 storage for a 20-day voyage in 2024 (m^3)	2,608.8 (130 ISO tank containers)	388.0	581.4
Tank capacity for CO_2 storage for a 20-day voyage in 2025 (m^3)	2,713.1 (135 ISO tank containers)	420.4	678.2

This study shows that the design of the size of the LCO_2 storage tank depends on:

- Vessel's level of energy efficiency, i.e., the better the energy efficiency of a vessel, the lesser CO_2 it emits and hence a smaller storage tank is required.
- Frequency of availability of liquid CO_2 offloading capabilities. The higher availability of offloading point at various ports, the smaller onboard storage is needed.
- Storage tank type and condition.
  - This will also depend on the onshore liquid CO_2 offloading capabilities.

- The amount of CO_2 emission reduction for CII compliance.
- The amount of CO_2 capture required for overall CO_2 emission reductions from the ship.

2.4.3 Selected LCO_2 Storage Capacity

For vessels to achieve compliance with the CII requirements, they need to maintain a CII rating of C or above. This means that not all the CO_2 generated by the vessel is required to be captured through the OCCS to achieve its required CII compliance. As depicted in Table 2.22 for a 20-day voyage, to meet the CII compliance in year 2025, the sample Panamax container ship will need storage tank capacity of 2713 m^3, the sample Panamax Bulk carrier will require storage tank capacity of 420 m^3 and the sample LR2 Tanker will require storage tank capacity of 678 m^3. However, it needs to be borne in mind that as annual incremental CII reduction factor increases every year, and so will the amount of CO_2 required to be captured and consequently the capacity of the storage tank.

The overall CO_2 emission reduction for a 20-day voyage with a 70% CO_2 capture rate, Panamax container ship (Table 2.13), Panamax bulk carrier (Table 2.14) and LR2 tanker (Table 2.15) will require storage tank capacity of 4000m^3, 1300m^3 and 1900m^3 respectively.

In the initial years, it is not expected that the shipping industry will look into 100% carbon capture and will more or less follow the regulatory obligations in designing the onboard carbon capture system storage capacities. Accordingly, for purpose of the study, storage tank capacities of 300 m^3 to 2000 m^3 have been selected for all three vessel types to provide a good representation of the general size of storage tanks expected onboard ships for LCO_2 storage. This storage capacity is based on practical considerations such as suitable size of the tank for the vessel, capture rate, duration of voyage, potential loss in cargo capacity and the CAPEX involved.

2.4.4 BOG Generation

Handling of LCO_2 leads to generation of a variable amount of BOG during operations including the vapour produced during sea transport by ambient heat penetration in the system due to temperature difference, and in case of sea transport due to the sloshing of the LCO_2 in the tanks.

It has been highlighted that rate of BOG is also affected by distance travelled, level of impurities in storage tank, tank pressure design and operational modes [10].

In LNG containment applications, the rate of BOG per day is around 0.1-0.15% which over a 20-day voyage produces undesirable amount of such gas. No exact values for boil-off rate per day of CO_2 is stated in literature, however 0.15% has been deemed suitable [11].

Factors that affect generation of BOG during static operations are provided in Table 2.23.

Table 2.23 – Factors affecting CO_2 BOG generation

Factor	Condition to reduce BOG	Remarks
Ambient temperature	Low	Lower ambient temperature results in lower heat influx, and hence, BOG.
Thermal resistivity and thickness of insulation	High	Results in lower BOG. Thickness is a trade-off between material cost and resulting reduction of boil-off.

Factor	Condition to reduce BOG	Remarks
CO_2 level in the tank	High	Low filling level in tank leads to a higher evaporation rate of the liquid.
Capacity of storage tank	Low	Assuming same absolute filling amount, smaller tanks exhibit lower rate of pressure build up due to BOG within the vessel.

An assessment of the BOG generated on the CO_2 storage tanks and the timeframe for pressure to increase to pressure relief valve (PRV) set pressure was carried out. The transient simulations required for this assessment were developed in Aspen HYSYS (Version 14) which is a chemical process simulator used to mathematically model chemical processes.

The following assumptions were made for the assessment:

- Fluid is assumed as pure CO_2 with no impurities.
- Ambient temperature: 45°C
- Still air, no wind
- Heat loss – detailed in Table 2.24 (including convection and conduction)

Table 2.24 – Conductive properties of storage tank

Conductive Properties	Metal	Insulation
Thickness (m)	0.050	0.250
Specific heat capacity Cp (kJ/kg-C)	0.473	1.200
Density (kg/m^3)	7801	45.00
Conductivity (W/m-k)	45.00	2.300e^{-002}

The specifications of the storage tank considered for the BOG calculation are provided in Table 2.25.

Table 2.25 – Storage tank specifications

Specification	Value
Internal Diameter (m)	10.06
T-T Length (m)	15.06
Shell Thickness (mm)	50.00
Capacity (m^3)	1199
Heads Type (m^3)	Flat
Liquid Volume at Simulation Initiation	1,000
Insulation Type	PU Foam
Insulation Thickness (mm)	250

Note: The tank dimensions are not intended to represent a recommended tank dimensions but merely for simplicity for the assumptions to carry out the BOG approximate calculations.

The BOG calculations were done for the five different pressure and temperature initiation conditions, and the results are tabulated in Table 2.26.

Table 2.26 –BOG simulation

Simulation Cases					
Case No	Initiation Pressure (barg)	Initiation Temperature (°C)	PRV Set Pressure (barg)	Time to reach PRV Set Pressure (days)	Time to reach PRV set pressure considering 45% safety factor (days)
1	6	Saturation	8	69.2	38
2	7	Saturation	8	33.4	18.4
3	15	Saturation	18	75.3	41.4
4	6	Saturation	18	356.6	196.1
5	10	Saturation	18	217.6	119.7

To be conservative and considering the various limitations and uncertainties about:

i. sloshing,

ii. convection due to wind,

iii. heat transferred through the vessel supports.

It has been considered necessary to incorporate a minimum 45% safety factor, based on experience and knowledge, into the total time required for the onboard captured CO_2 storage tank to reach the PRV set pressure. This will aid in the ship's OCCS design considerations, determining the need for a reliquefaction plant to be installed to prevent CO_2 venting.

In conclusion, it may be generally expected that ships fitted with LP CO_2 storage tanks will require to be fitted with additional means to handle the BOG, such as a reliquefaction plant, and ships fitted with MP CO_2 storage tanks could handle the BOG within the tank as long as the off-loading operation is done at intervals not exceeding approximately 35 days.

2.5 Selected Design Profile

The maritime industry is pursuing the optimisation of OCCS technology, aiming to utilise it as a pathway for decarbonisation. This involves retrofitting existing assets with OCCS and integrating OCCS into new builds, all while minimising the trade-off in cargo carrying capacity.

Presently, storing captured CO_2 in the liquid phase under either LP or MP conditions is considered viable. However, a consensus regarding the preferred approach is yet to be established. The decision-making process will involve finding the right balance between several factors, including the costs of CAPEX and operational expenditure (OPEX), structural integrity, vessel space limitations, potential cargo capacity reduction, and compatibility with onshore specifications.

LP conditions closer to the CO_2 triple point (5.18 bara, -56.6°C) offer optimal storage tank volume utilisation due to the higher density of liquid CO_2. However, further deliberation is necessary, particularly to address the risk of dry ice formation and to select suitable materials throughout the entire OCCS based on the operational design's pressure and temperature requirements.

Based on the literature review conducted and considering all pertinent aspects, the operational envelope outlined in Table 2.27 has been used in this study as the basis of design for LCO_2 storage and offloading from ships in the subsequent chapters.

Table 2.27 – Selected design profile for the study

Voyage Criteria	Panamax Container ship	Panamax Bulk Carrier	LR2 Tanker
Voyage (days)	8-20 days	8-20 days	8-20 days
Frequency of unloading	Once or twice a month		
Estimated time for transfer	8 hours		
Storage arrangements	**Panamax Container ship**	**Panamax Bulk Carrier**	**LR2 Tanker**
Storage tank type	Type C/ ISO tank containers	Type C	Type C
Storage condition	LP or MP or ISO tank containers	LP or MP	LP or MP
Location onboard	Type C – Below deck ISO tank containers – Above deck	Below deck	Above deck
Tank size	300 – 2,000 m^3	300 – 2,000 m^3	300 – 2,000 m^3
Tank material	Carbon steel/ Stainless steel/Stainless steel inner, Carbon steel outer		
Handling equipment	BOG handling – Designed for pressure rise endurance up to 15 days. Liquefaction plant may be used for reliquefaction. Pumping – submerged transfer pumps, booster pumps, spray pumps		
Storage and Offloading Conditions			
LP	5.7 to 10.0 bara (Normal WP: 8.0 bara)	-54.3°C to -40.1°C	1,170 to 1,117 kg/m^3
MP	14.0 to 19.0 bara (Normal WP :16.0 bara)	-30.5°C to -21.2°C	1,078 to 1,037 kg/m^3
ISO Tank Container 20ft capacity: 20 m^3 net	18.0 to 24.0 bara (Normal WP: 22.0 bara)	-25.1°C to -20.1 °C	1,057 to 1,032 kg/m^3

2.6 Location of Tanks

The location of LCO_2 storage tank will vary based on design considerations of each type of vessel, but the general options of placement of storage arrangements for container ships, bulk carriers and tankers are described in this section.

Container Ship

There are two concepts of storage arrangements that have been found as suitable for LCO_2 storage on container ships – Type C tanks (Figure 2.5) and Cassette arrangement with ISO tank containers (Figure 2.6).

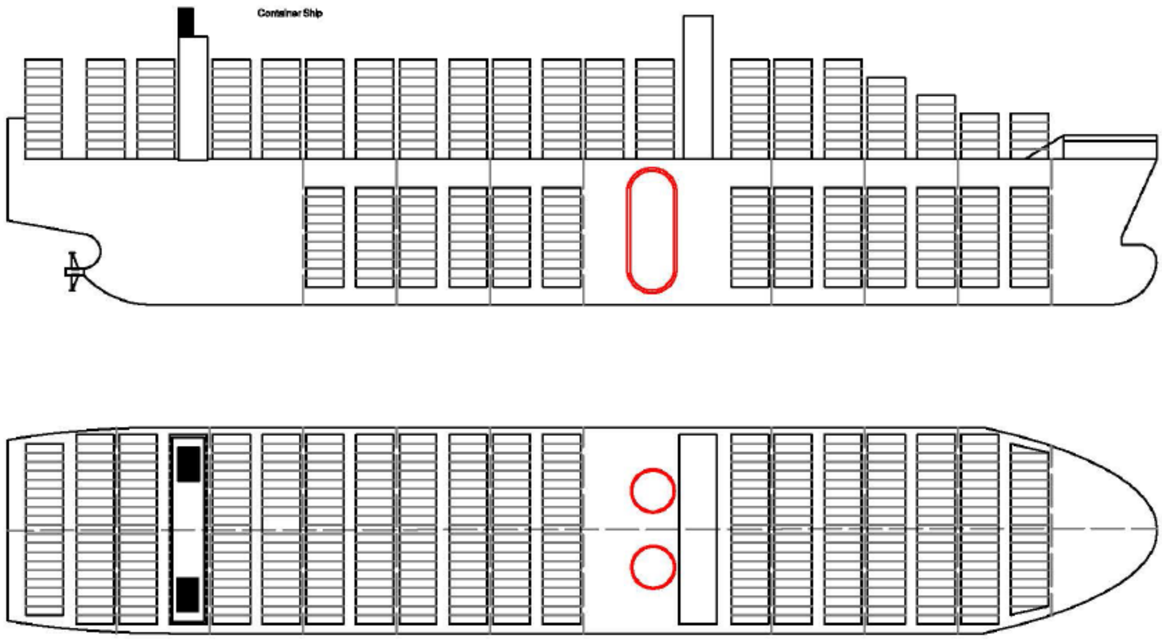


Figure 2.5 – LCO_2 storage tank (Type C tank) location for container ships below deck

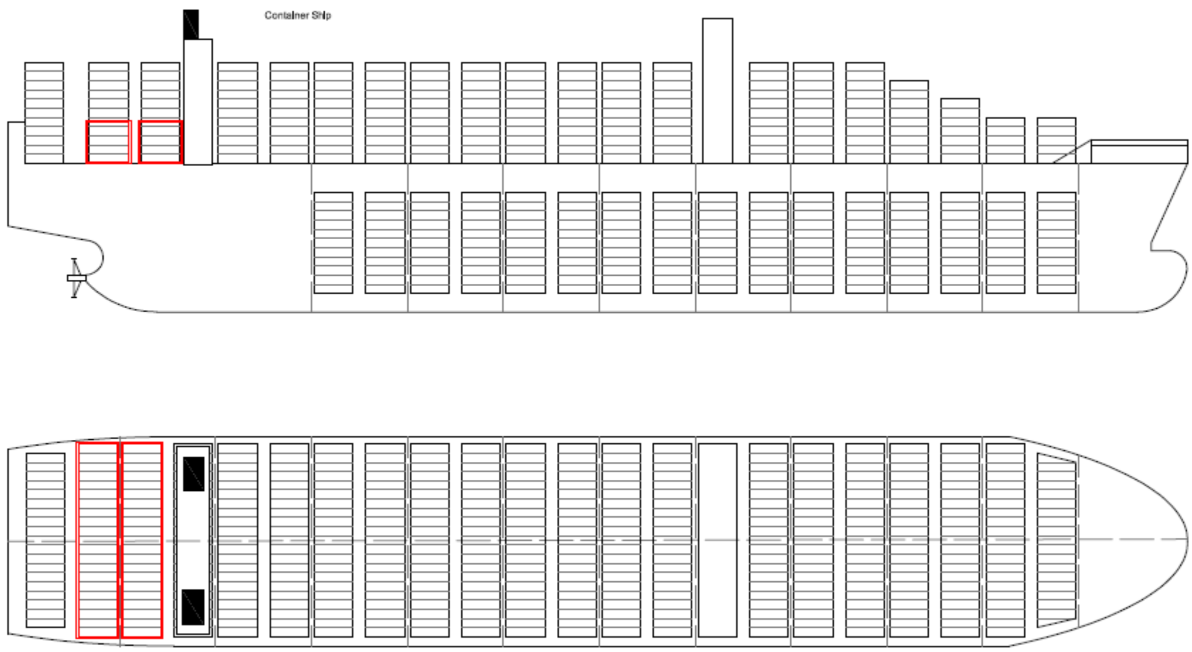


Figure 2.6 – LCO_2 storage tank (ISO tank containers) location for container ships above deck

Bulk Carriers

Type C tanks have been found as suitable for LCO_2 storage on bulk carriers both above deck and below deck (Figure 2.7 and Figure 2.8).

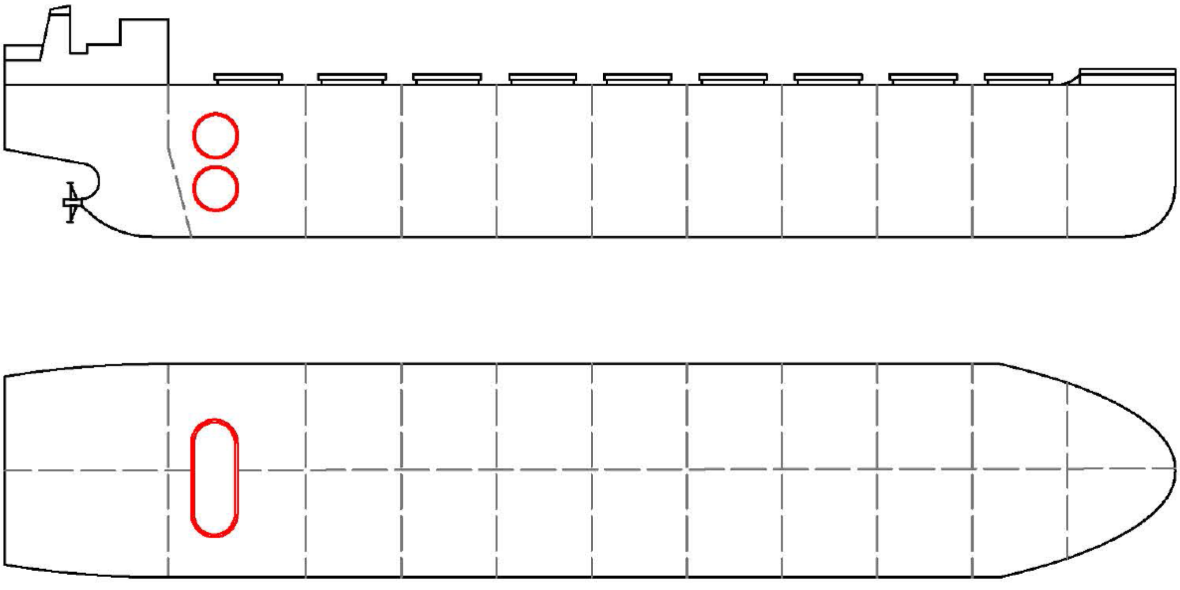


Figure 2.7 – LCO_2 storage tank (Type C tank) location for bulk carriers below deck

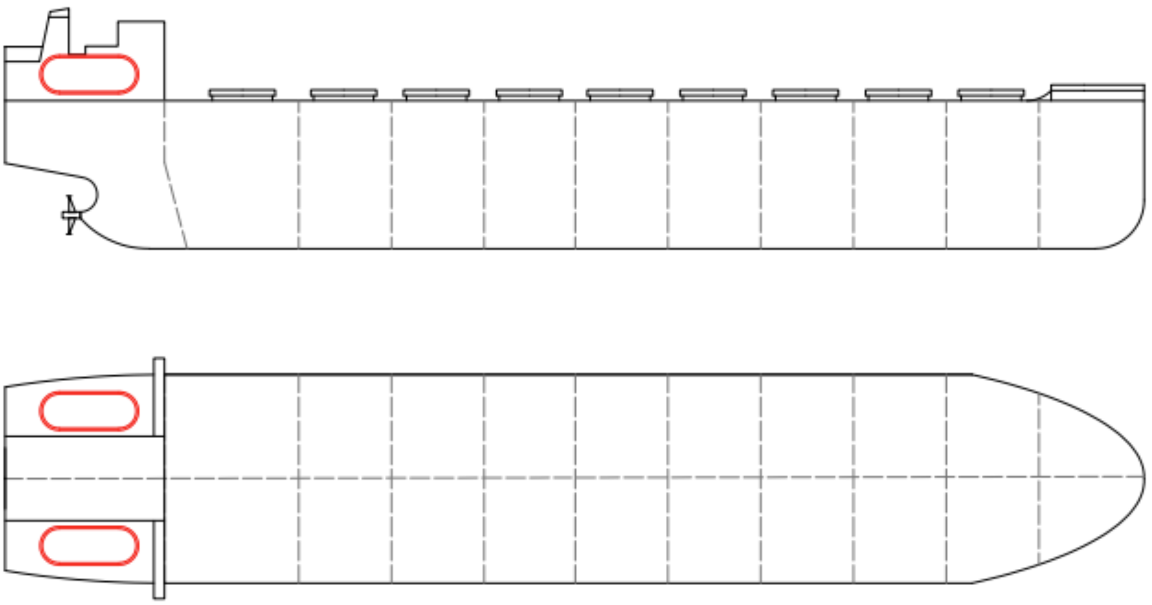


Figure 2.8 – LCO_2 storage tank (Type C tank) location for bulk carriers above deck

Tankers

Type C tanks have been found as suitable for LCO_2 storage on tankers above deck (Figure 2.9).

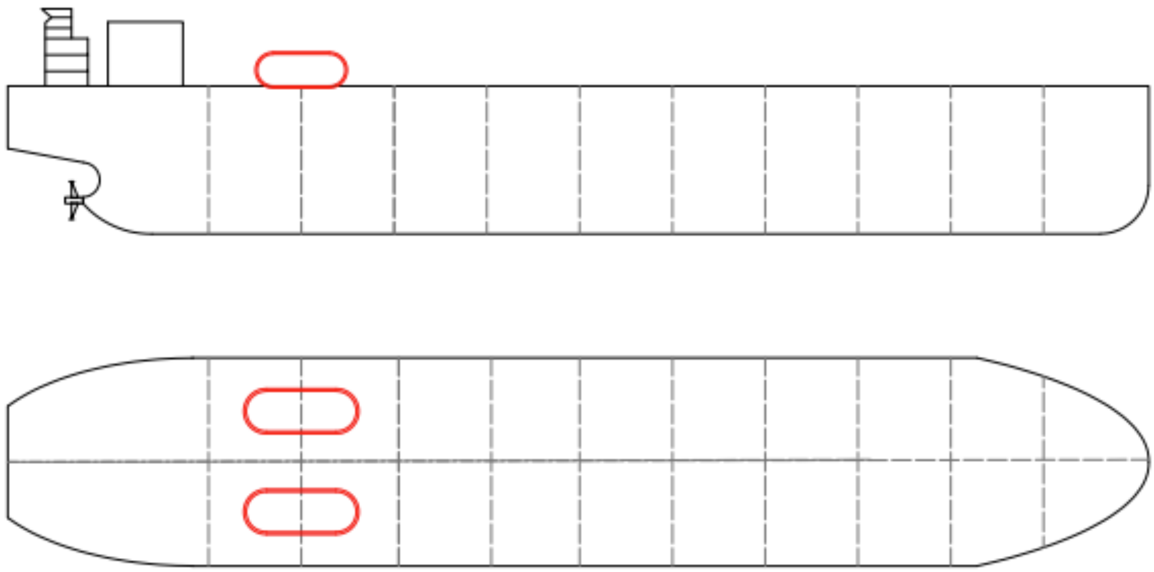


Figure 2.9 – LCO_2 storage tank (Type C tank) for tankers above deck

2.7 LCO_2 Storage Tank Handling Equipment and Maintenance Regime

Specific handling equipment will be needed onboard ships for storage, handling and offloading of LCO_2. This section provides a brief description of the equipment and its maintenance regime drawing the knowledge from LPG / LNG ship's equipment.

2.7.1 LCO_2 Storage Tank Handling Equipment

2.7.1.1 Discharge Pump

The discharge pump will be either of the 'submerged' electric type (Figure 2.10) or 'deepwell' type. The multistage centrifugal pump will be located at the bottom of the tank driven by a submerged electric motor for the 'submerged' electric type pump and driven by an electric motor located on top of the tank via a drive shaft for the 'deepwell' pump. The pump material and discharging pipes shall be stainless steel with suitable corrosion resistance for LCO_2 and its impurities.

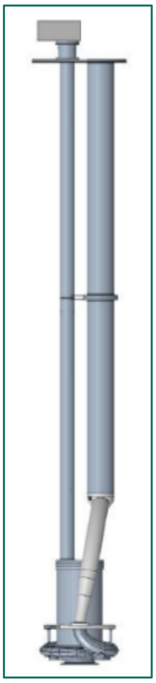


Figure 2.10 – Submerged Electric Type Discharge Pump (Courtesy – Alfa Laval)

Figure 2.11 – Discharge Booster Pump

2.7.1.2 Booster Pump (External Discharge Pump)

Booster discharge pumps (external to the storage tank) will be needed for discharging to storage facilities having higher pressure than the storage pressure onboard. They are typically a horizontal multistage unit driven by an electric motor (Figure 2.11). The pump material shall be stainless steel with suitable corrosion resistance for LCO_2 and its impurities.

2.7.1.3 Reliquefaction Plant

Ships fitted with LP LCO_2 storage tanks may require to be fitted with a reliquefaction plant to manage the BOG. It is not expected that MP storage tanks system will require a reliquefaction system considering off-loading of the LCO_2 take places at intervals not exceeding 35 days (see section 2.4.4).

Three configurations are available for the re-liquefaction plants as below.

Direct Reliquefaction Plant

The reliquefaction plant may be of direct reliquefaction process type where the BOG CO_2 itself is used as the refrigerant (Figure 2.12). The reliquefaction plant may use two or more compression stage cycles with inter-stage cooling as the compression ratios are high. This is necessary to limit the compressor discharge temperature which increases significantly with the higher compression ratio.

Boil-off vapours from the storage tank are drawn off by the compressor. Compression increases the pressure and temperature of the vapour. The high temperature allows it to be condensed in the water-cooled condenser. The condensed liquid is flashed back to the tank via an expansion valve. The liquid/vapour mixture being returned the storage tank may be either distributed by a spray rail at the top of the tank or taken to the bottom of the tank to discourage re-vaporisation. The spray rail is normally used when the tank is empty and bottom discharge when the tank is full.

A direct reliquefaction plant maybe used in case that it is necessary to separate the reliquefaction system from the CO_2 reliquefaction system.

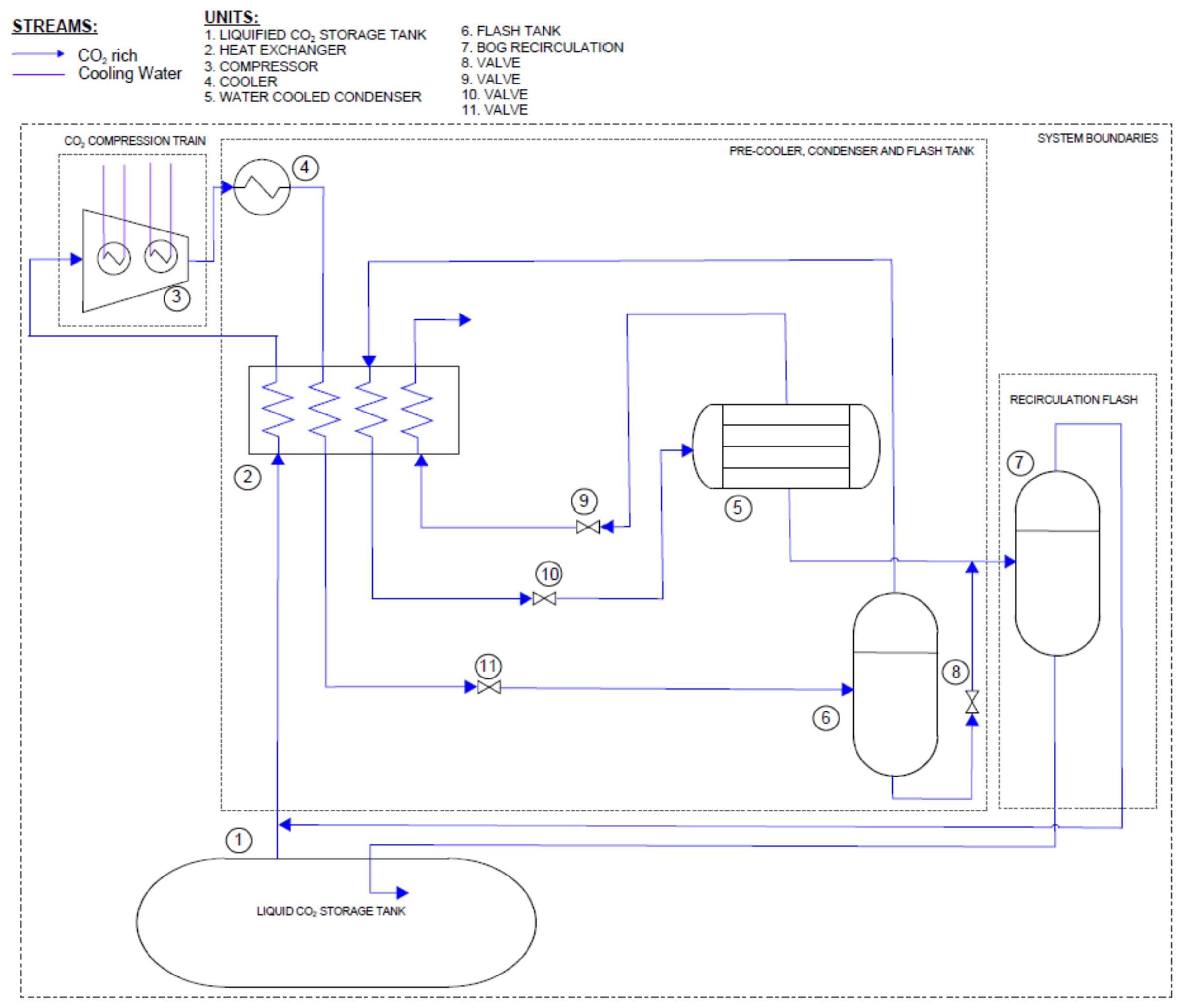


Figure 2.12 – Direct reliquefaction plant

The compressors are typically of the multistage, oil-free type and capacity control is achieved by altering the way the compressor operates. The stages can be in series, in parallel, or bypassed depending on the required capacity.

With this reliquefaction system, it is expected that the reliquefaction capacity will not reach 100% and some losses from the stored LCO_2 will occur. To increase the efficiency of the reliquefaction, the system can add additional different separators and cold heat recovery processes.

Cascade Direct Cycle Reliquefaction Plant

In the case that full reliquefaction of the CO_2 vapour is required without any losses, the alternative will be to install a cascade direct cycle where the CO_2 vapour is liquefied by an external refrigeration cycle, using ammonia (NH_3) as the refrigerant (Figure 2.13).

The boil-off vapours enter the CO_2 compression train to undergo several stages of intercooled compression to achieve a pressure suitable for reliquefaction in the heat exchange.

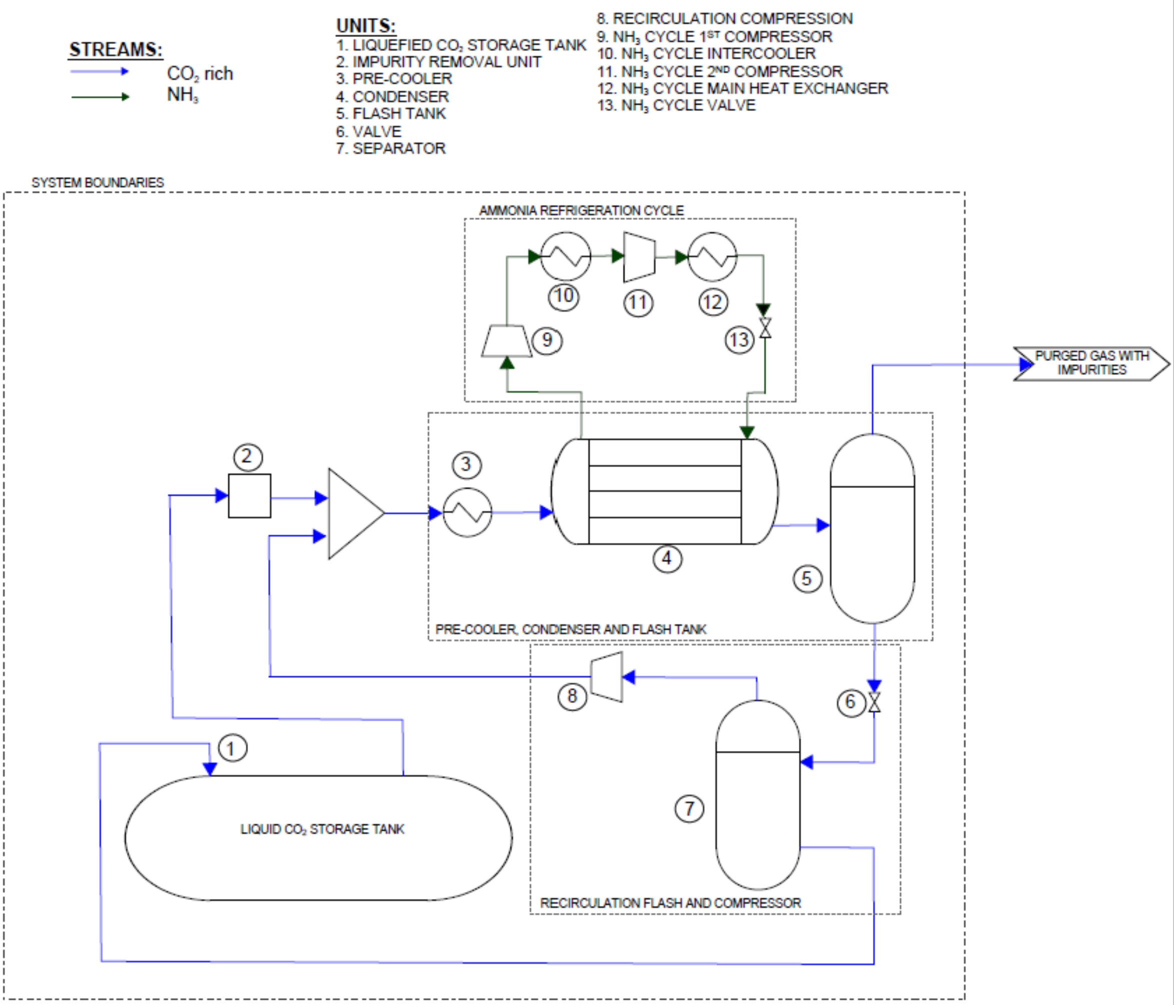


Figure 2.13 – Cascade direct cycle reliquefaction plant

It is worth noting that the refrigeration circuit used for condensing compressed CO_2 vapours is selected to be an ammonia-based two-stage vapour compression cycle with an intercooler and a main heat exchanger (condenser). The NH_3 is only used as coolant in the condenser while all the other heat exchangers in the process are water-cooled, including the intercoolers of the compression train, the pre-cooler, as well as the intercooler and the main heat exchanger of the NH_3 refrigeration cycle.

Reliquefaction System Integrated within the CO_2 Liquefaction Plant

In the case of the system being integrated within the liquefaction system of the CO_2 stream generated from the consumers, the CO_2 is liquefied by an external refrigeration cycle, using NH_3 as the refrigerant. This is subject to a proper suitable process design integrating the BOG out stream generated from the LCO_2 storage tank, considering flow, temperature and pressure, into the re-circulated BOG generated from separator process tank in the reliquefaction system (Figure 2.14).

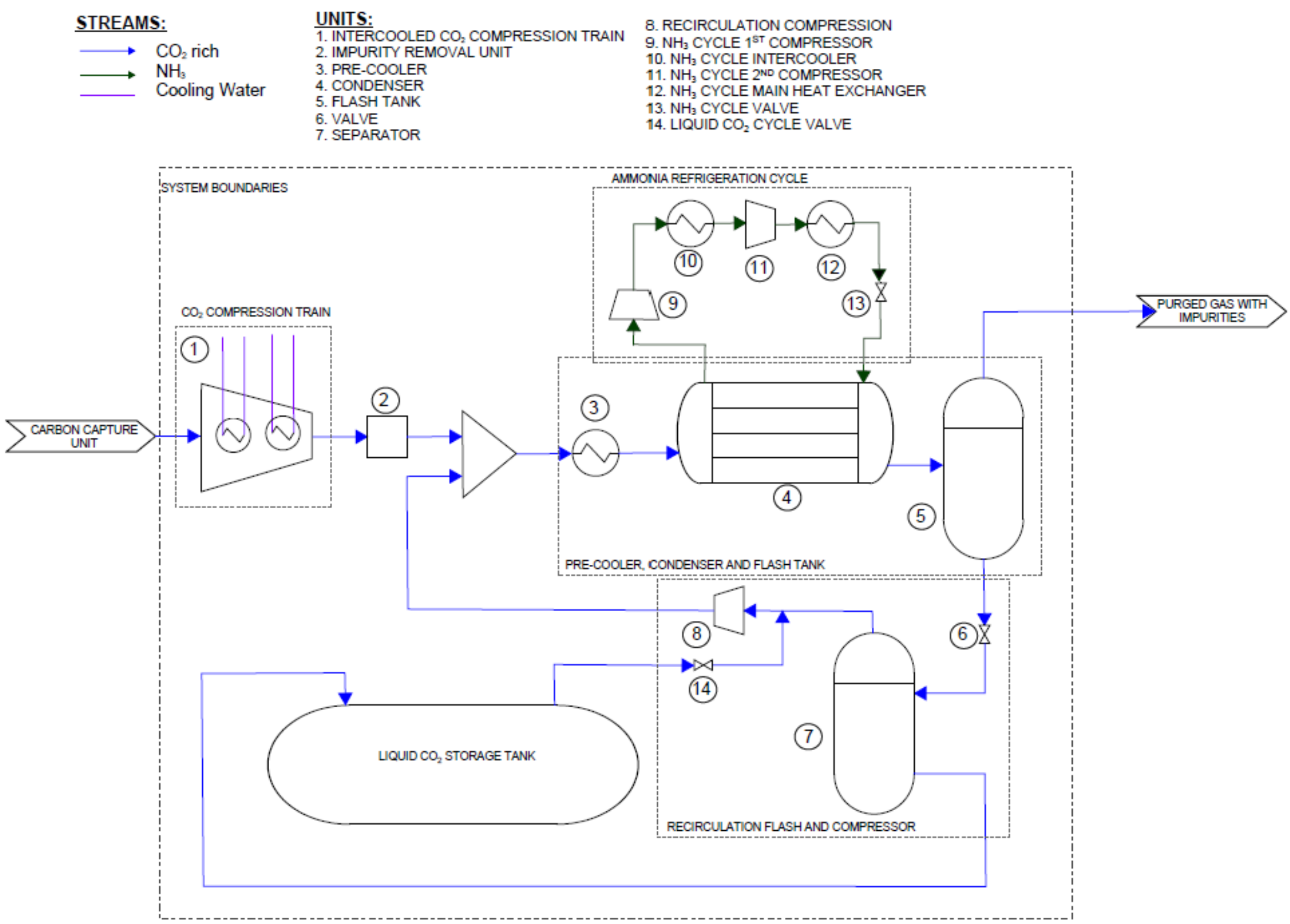


Figure 2.14 – Reliquefaction system integrated within the CO_2 liquefaction plant

2.7.1.4 Compressor

The compressor is the heart of the reliquefaction plant and could be either reciprocating or screw type. The compressor will be oil-free type to avoid contamination of CO_2 gas quality.

The reciprocating type compressor cylinder is cooled by forced water circulation to minimise temperatures, increasing efficiency and reliability. Pistons are made of stainless steel and piston rings of polytetrafluoroethylene (PTFE). The crosshead bearings and crank-shaft are oil lubricated. Capacity control of the compressor is achieved by lifting suction valves during the compression stroke.

The screw type compressor is a rotary compressor that compresses CO_2 through the rotation of the twin-screw meshing rotors. The compression space gradually reduces, compressing the volume of CO_2. The compressor casing carries the suction and discharge ports. Capacity control of screw compressors can be achieved in a number of ways. The most common is the use of a sliding valve which effectively reduces the working length of the rotors. This is more efficient than suction throttling. Screw compressors consume more power than reciprocating compressors.

2.7.1.5 Heat Exchanger – Condenser

Heat exchangers in the system may be either shell and tube type or plate type.

1) Shell and Tube Type Heat Exchanger

This is the most common design with a shell accompanying several tubes and the flow of fluid to be cooled is mainly through tubes, whereas the secondary liquid flows over the tube inside the shell. Shell and tube type heat exchanger is extremely economical to install and easy to clean; however, the frequency of maintenance is higher than other types. In this heat exchanger, the complete shell is fitted with a tube stack. There are two end plates which are sealed on both the sides of the shell and a provision is made at one end to cater for the expansion. The cooling liquid passes through the tubes which are sealed on either end into the tube plate. The tubes are secured in the tube plate by bell mouthing and expansion. The shell is enclosed with water chambers which surround the tube plates completely. The coolers could either be single pass or double pass exhibiting the flow of cooling liquid. Gaskets are fitted between the tube plates and the shell; similarly, between the tube plate and the end cover to cater to the leakages from the cooler.

2) Plate Type Heat Exchanger

Plate type heat exchanger consists of thin corrugated plates joined in parallel together, creating a cavity for fluid flow inside it. The metal plates are sealed from each other by nitrile rubber joints. Alternate sides of the plate carry two different fluids, between which, heat transfer is carried out. The plate type heat exchanger is more expensive than shell and tube type, but the maintenance cost is much lower. The efficiency of plate type is higher than shell and tube type for the same size of the unit and can withstand higher pressure. The plate type coolers can be opened easily for cleaning and are thus convenient to install and clean as minimum space is required for their installation.

2.7.1.6 Pressure Build-up Unit (PBU)

Pressure build-up unit (PBU) is essentially a heat exchanger in the form of a heater that will be needed to produce CO_2 pressurised vapour when vapour return is not available from the shore terminal or from the LCO_2 receiving vessel. The capacity of the PBU unit should be sufficient to meet the transfer demand and maintaining the storage tank pressure during discharging (offloading) of LCO_2, preventing the vapour to reach below the triple point.

2.7.1.7 Instrumentation, Controls and Safety Systems

The LCO_2 storage system will have instrumentation, controls, alarms and safety systems to assist the crew in ship operations, helping to prevent dangerous situations arising as well as mitigating the consequences of system malfunction and human error. Modern ships will have computer-based interfaces for the control systems.

The main control, alarm and safety systems for LCO_2 storage are summarised as:

- Tank level indication and control,

- Tank overflow control,
- Tank pressure indication and control,
- Tank vacuum protection,
- Temperature indication,
- Gas detection,
- Emergency Shutdown (ESD) System
- In addition, a ship shore link may also be specified and linked to the ship's ESD system.

2.7.1.8 Piping Systems and Valve Requirements

The piping system will be suitably designed for the design pressure and temperature. The material would need to be stainless steel with grade SS316L stainless steel as a suitable choice as it is an easily weldable material that has a proven service history with good corrosion resistance. Careful consideration should be given to valves and other components in the piping system for suitability for captured LCO_2 and its corrosive nature. Piping insulation of appropriate materials and specifications shall be in place for LCO_2 pipelines to prevent condensation and icing. In order to prevent overpressure situations, each section of liquid piping that may be isolated with liquid CO_2 in the lines e.g., between two closed valves (manual valves, control valves, check valves) or a valve and a blank flange is to be provided with a relief valve set to the design pressure. The relief valves shall be installed on a riser pipe extended from the cold LCO_2 piping to create vapour trap, prevent water ice formation and drain any condensation.

2.7.1.9 Storage Tank Relief Valve

Requirements from IGC Code may be followed for the Type C storage tank relief valves. The code requires that each cargo tank be fitted with at least two relief valves of adequate capacity. The valves are to be prototype tested to ensure they meet the minimum flow requirements under the design conditions and are to be sized for the vapour generated under exposure to fire conditions. When calculating the vapours generated under fire conditions correction factors are applied for the varying types and location of tanks for example degree of insulation, above or below the deck. The valves are to be connected to the highest point in the tank but must also remain in the vapour phase with the ship listing up to 15° and with a trim of 0.015L. Means for isolating the PRVs will need to be fitted and isolation operation to be arranged in a mode that this can be done safely in normal and emergency operation. As per industry guidance, it is recommended to have a remote isolation on the pressure safety valve (PSV) inlet to prevent continuous depressurisation in case of the relief valve not closing. This is to prevent reaching triple point and consequent solidification of the tank content. The vent piping of the relief valve has to be led outside the confined space.

2.7.2 Maintenance Regime

As the LCO_2 system storage and handling system will not be available for maintenance during operations, a robust maintenance regime as per maker's instructions should be rigorously followed for smooth operations and to avoid unexpected breakdowns creating hazardous situations. Usually, the maintenance is planned as per dry-dock schedule of the vessel. Following generic maintenance regime is based on various maker's instructions. The specific instructions and overhaul interval hours provided by the ship's specific equipment maker should be followed for each ship.

2.7.2.1 Reliquefaction Plant

At intervals recommended by the makers

- Function test of the safety and control instrument,
- Check set points of the safety instruments.

2.7.2.2 Compressor (Reciprocating Type)

At intervals recommended by the makers and at least once every five years.

- Visual check of oil scrapers and piston rod surface (without dismantling).
- Oil change, clean oil strainer and crankcase of the compressor (first time after 4000 running hours).
- Check valves, lanterns and gaskets.
- Check clearance between guide bearing and piston rod (with feeler gauge or dial gauge).
- Check gland rings and replace if required - In case of gas leaks to intermediate piece.
- Check oil scrapers and piston rod surface - In case of insufficient function of oil scrapers.
- Check clearances of: crankshaft bearing, connecting rod bearing, crosshead pin bearing and crosshead without removing (by feeler gauge or dial gauge).
- Check tightening of connecting rod bolts.
- Check piston clearance by feeler gauge and the preload force / tightening of piston nut.
- Check pretension of piston crowns (piston with diameter 480mm and larger).
- Check alignment of flexible coupling – each time after coupling of electric motors.
- Remove some crankshaft bearings, connecting rod and crosshead pin bearings for inspection (spot check).
- Clean the cooling water chamber of the frame and cylinder. Check the corresponding gaskets - According to fouling factor and water treatment.
- Check the crankshaft seal (replace if necessary) - If shaft seal is leaking.

2.7.2.3 Heat Exchangers

Interval of at least every five years:

- Cleaning as per fouling condition monitoring.
- Internal inspection.
- Pressure Test, if considered necessary.

2.7.2.4 Discharge Pump (Submersible or Deep Well Type) and Booster Pump

At intervals recommended by the makers and at least one every five years:

- Bearings - Replace antifriction bearings.
- Mechanical seals - Mechanical seals will always leak a bit, due to the way they work. In the event of substantial leaks: replace the mechanical seals and their auxiliary seals and check the integrity of the auxiliary systems.

- Internal Inspection – Internal inspection of impeller, mouth rings and casing. Renew all gaskets and O-rings. Replace wear rings. Replace all bearings. Replace static seal.

2.7.2.5 Pressure Relief Valve

At interval of at least once every five years:

- Dismantle and replace any worn / corroded parts.
- Pressure Setting Test.

2.8 References

[1] H. A. Baroudi, "A review of large-scale CO_2 shipping and marine emissions management for CCUS," 2021.

[2] Vermeulen T N, "Knowledge sharing report – CO_2 Liquid Logistics Shipping Concept (LLSC): Overall Supply Chain Optimization," 2011.

[3] A. P. (. K. Richard Doctor (United States), "Chapter 4: Transport of CO_2," in *IPCC Special Report on Carbon dioxide Capture and Storage*, 2005, pp. 179-194.

[4] WorleyParsons, " CCS learning from the LNG sector - A report for the Global CCS Institute," 2013.

[5] Decarre S, Berthiaud J, Butin N, Guillaume-Combeca, "CO_2 maritime transportation. Int J Greenh Gas Control," 2010.

[6] Haugen HA, Eldrup NH, Fatnes AM, Leren E., "Commercial Capture and Transport of CO2 from Production of Ammonia. Energy Procedia.," 2017.

[7] Aspelund A, Mølnvik MJ, De Koeijer G., "Ship Transport of CO_2- Technical Solutions and Analysis of Costs, Energy Utilisation, Exergy Efficiency and CO_2 Emissions. Chem Eng Res Des," 2006.

[8] Seo Y, Huh C, Lee S, Chang D., "Comparison of CO_2 liquefaction pressures for ship-based carbon capture and storage (CCS) chain. Int J Greenh Gas Control," 2016.

[9] Bureau Veritas Study - Feasibility Study and Design. Installing Carbon Capture and Storage Units on Existing Ships. June 2023 [Online]. Available: https://marine-offshore.bureauveritas.com/insight/our-publications/installing-carbon-capture-and-storage-units-existing-ships-feasibility-study-and-design

[10] Z. A. K. I. Hasan MMF, " Minimizing boil-off losses in liquefied natural gas transportation. Ind Eng Chem Res.," 2009.

[11] C. Y. K. M. Jeon SH, "[Review on Boil-Off Gas (BOG) Re-Liquefaction System of Liquefied CO_2 Transport Ship for Carbon Capture and Sequestration (CCS). Int J Air-Conditioning Refrigeration," 2016.

[12] A. P. (. K. Richard Doctor (United States), "Chapter 4: Transport of CO_2," in *IPCC Special Report on Carbon dioxide Capture and Storage*, 2005, pp. 179-194.

3. Onboard Captured Liquefied CO_2 Offloading Concepts

3.1 Overview

This chapter describes the selection and development of four outline concepts for offloading onboard captured carbon dioxide in the form of liquefied carbon dioxide (LCO_2). The concepts have been developed to aid understanding, risk assessment and cost estimates as required within the wider study.

These concepts are not intended to represent the only solutions available for each scenario. The reader should use them as a guide to the range of solutions available and how they interface with each scenario. The scope of each concept starts downstream of the onboard carbon capture equipment with the CO_2 liquefied, ready for onboard storage. The concept concludes at in-port storage which is either onshore or floating depending on the scenario.

The chapter gives an outline on how the scenarios were filtered to reflect the most likely short-term applications whilst covering, as much as possible, the range of permutations which could arise within the scope of the study.

Each concept is described by an equipment list, images of equipment where applicable and a process flow diagram (Appendix C) from capture vessel storage to LCO_2 receiving vessel / shore storage. A narrative is also given of each solution to further aid understanding along with the drawings.

3.2 LCO_2 Offloading Scenarios

3.2.1 Introduction

This chapter presents four priority offloading concepts (See Table 3.1) that were developed for this study. These concepts represent the most practical and cost-effective solutions for near-term applications (around five-year time) for offloading onboard captured and liquefied CO_2. Additionally, between them, the concepts cover the key offloading steps for a wider range of offloading solutions, so they can be used as building blocks to explore and inform design and operational considerations more broadly.

3.2.2 Inputs

The priority concepts have been developed based on:

i. The 'Annex 2 Overview of scope of Invitation for Proposals (IFP) on LCO_2 offloading" provided by the Global Centre for Maritime Decarbonisation (GCMD) in the project IFP. See Figure 3.1.

ii. Selected operational profile for the study reported in chapter 2 of this report on onboard storage of captured CO_2. See Table 2.27.

iii. An internal workshop to review each offloading permutation and its relative feasibility.

iv. Engagement with the GCMD and study partners (including Port of Rotterdam, the Maritime & Port Authority of Singapore (MPA) and Jurong Port) to validate the shortlist.

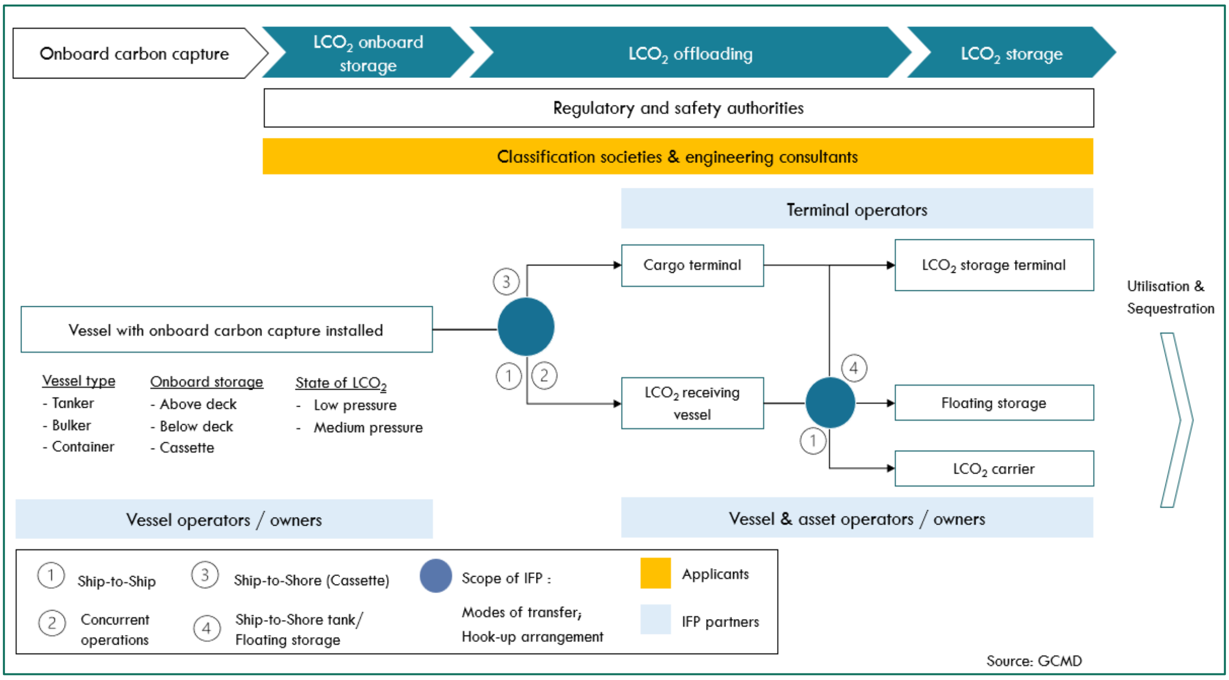


Figure 3.1 – Overview of scope of IFP on LCO_2 offloading

3.2.3 Assumptions

The key assumptions made to consider high priority offloading scenarios are:

i. The LCO_2 offloading concepts are focussed at near-term applications, aligned with the LCO_2 volumes arrived at in chapter two of the report.

ii. The offloading concepts (infrastructure and operations) will be focussed primarily on the upper envelope of the LCO_2 capacities (2000m^3), but the concept performance will be considered at a high-level for the lower envelope (300m^3) as well.

iii. The offloading concepts should try to minimise interruptions to port operations, be as low cost as practical (CAPEX and OPEX) and should minimise environmental/safety risks.

3.2.4 Shortlisted Concepts

The four offloading concepts shortlisted for the study are shown in Table 3.1. This chapter describes how these were considered as the four priority scenarios amongst the many permutations linked to Figure 3.1.

Table 3.1 – Four offloading concepts selected for the study

Concept No.	Cargo vessel type	Onboard Storage location	LCO_2 volume per offload	Conditions of LCO_2 in onboard storage	Primary Transfer	Secondary transfer
Concept 1	Tanker	Above deck	2000 m^3	Low pressure or medium pressure	Tanker to bulk liquid terminal	None
Concept 2	Bulk carrier	Above deck	2000 m^3	Low pressure or medium pressure	Bulk carrier to LCO_2 receiving vessel at anchorage	LCO_2 receiving vessel to floating CO_2 storage at anchorage
Concept 3	Bulk carrier	Below deck	2000 m^3	Low pressure or medium pressure	Bulk carrier to LCO_2 receiving vessel at anchorage	LCO_2 receiving vessel to bulk liquid terminal
Concept 4	Container ship	Above deck	300 m^3	ISO tank container pressure	Container ship to cargo term-inal (ISO tank container via Ship-To-Shore (STS) crane)	Cargo terminal to liquid bulk terminal storage

The study prioritised these four concepts because:

i. It is less likely that bulk carriers will, in the near-term, offload LCO_2 directly at their cargo berths. This would require provision of significant piping and storage infrastructure within dry bulk terminals, which could hinder port operations. It is also challenging to retrofit to existing terminals with such infrastructure.

ii. An infeasible quantum of cassette transfers (over 100) would hinder port operations if the upper envelope of the LCO_2 volume (2000m^3) is realised. CO_2 container operations would therefore impede on other freight. ISO tank container transfer is considered for the lower envelope (300m^3) only.

iii. Offload concepts from either bulker carrier or container ship type C tanks to an LCO_2 receiving vessel are likely to be similar enough in character to be represented by concept 2 & 3.

iv. The preference for secondary offloading from LCO_2 receiving vessels to floating CO_2 storage vs LCO_2 storage terminal will be highly location specific, so both modes warrant further consideration. It is to be noted that both options are potentially capital intensive.

v. It is less likely, particularly for near-term applications, that an LCO_2 receiving vessel will transfer to an LCO_2 carrier for onwards transport out of the terminal or port. The LCO_2 receiving vessel is more likely to directly transport the LCO_2 product out of the terminal or port itself.

vi. Tankers are more likely to prefer offloading LCO_2 at the same berth as they are offloading liquid cargo. This is due to operational parallels which reduce the number of operations during a port call and remove the need for an LCO_2 carrier or barge. This could present a less capital-intensive option for offloading.

vii. The position of tanks on bulk carriers has been refined to include a scenario with above deck storage and one with below deck storage. This ensures there is a concept covering the larger head difference with a below deck tank.

viii. Rather than considering only low or medium pressure offloading states for each offloading concept, the study will consider both pressure states in the subsequent chapters on design development.

These considerations are discussed in further detail in **Error! Reference source not found.**. Block Flow Diagrams (BFD) and Process Flow Diagrams (PFD) for scenarios 1 to 4 are given in **Error! Reference source not found.** and **Error! Reference source not found.** respectively. A narrative on how the concepts work are given in the following Section 3.3.

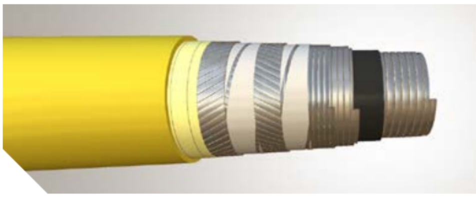
3.3 Process Descriptions

3.3.1 Equipment Description

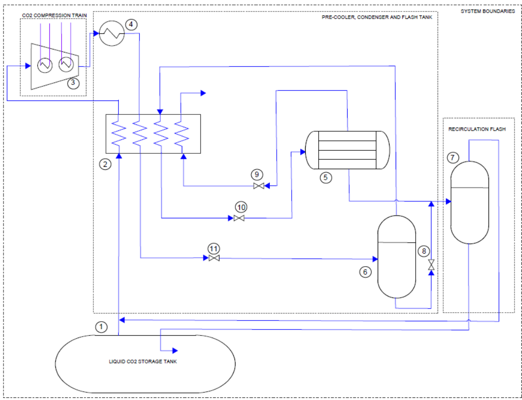
The process equipment required for LCO_2 offloading systems has been detailed in Table 3.2. This table provides the component name and typical sizes expected for the concepts defined in this report. Indicative images have also been provided to aid understanding.

Table 3.2 – Process equipment description

Item and Applicable Concept	Typical Specification	Visual Example
Onboard Offloading Pump (Discharge Pump) Concept 1 to 4	Pump is likely to be submersible type located inside the storage tank onboard ship. A range of options are available in the 37-250 m^3 /hr range to meet the offloading requirements	 [1]

Item and Applicable Concept	Typical Specification	Visual Example
Rigid and Flexible Insulated Piping Concept 1 to 4	Internal diameters ranging from 2" to 22" for flexible insulated pipe	 [2]  [3]
Loading Arm (or offloading boom) Concept 1 to 3	Typical design for a marine loading arm used for LNG bunkering has two hoses. The same design can be used to allow LCO_2 offloading and vapourised CO_2 return. For larger scale operation, individual loading arms may be used for each service.	 [4]
Vapour Return Compressor Concept 1 to 3	Pressure Ratios <2.5:1 Typical Volumetric Flow 2040 m^3/hr Pressure Deltas 1.3 bar (based on LNG vapour return compression. This will need to be adapted for CO_2)	 [5]

Item and Applicable Concept	Typical Specification	Visual Example
Liquid Bulk Terminal Storage Tank Concept 1 to 4	20,000 m^3 (20 X 1,000 m^3) 6-8 bar (Low Pressure)	 [6]
Custody transfer metering systems Concept 1 to 4	Based on ultrasonic or Coriolis cryogenic flow meters Uses from large scale ship unloading to bunkering and truck loading Consists of: • Flow Metering Skid • Metering Control Cabinets • Sampling and Analyser systems • Supervisory/Validation software	 [7]
Pressure Build-up Unit Concept 1 to 3	Heat exchanger mounted to tank to maintain tank pressure during liquid withdrawal	 [8]

Item and Applicable Concept	Typical Specification	Visual Example
Reliquefaction system/BOG Handling System Concept 1 to 3	Direct Reliquefaction type where the BOG CO_2 itself is used as the refrigerant. The liquefaction plant may use two or more compression stage cycle with inter-stage cooling. OR Cascade Direct Cycle Reliquefaction Plant where the CO_2 vapour is liquefied by an external refrigeration cycle, using NH_3 as the refrigerant	 Direct Reliquefaction type
ISO tank containers Concept 4	Stainless Steel Inner Carbon Steel Outer 18-24 bara -20 to -25 °C 20 ft Capacity = 19 m^3 net	 [9]

3.3.2 Concept 1 – Ship-to-Liquid Bulk Terminal

Carbon capture units onboard ships will treat the flue gas to separate the CO_2. The CO_2 is liquefied and transferred into the LCO_2 storage tank onboard the ship, which is located above deck for this concept. To manage boil-off from this tank, if needed there will be a Boil-Off Management System provided. This will function by a vapour line running from the top of the tank leading to a reliquefaction plant where the vapours will be reliquefied and returned to the LCO_2 storage tank in liquid form. Alternatively, storage tank insulation may provide sufficient endurance to handle the BOG for the design operating profile.

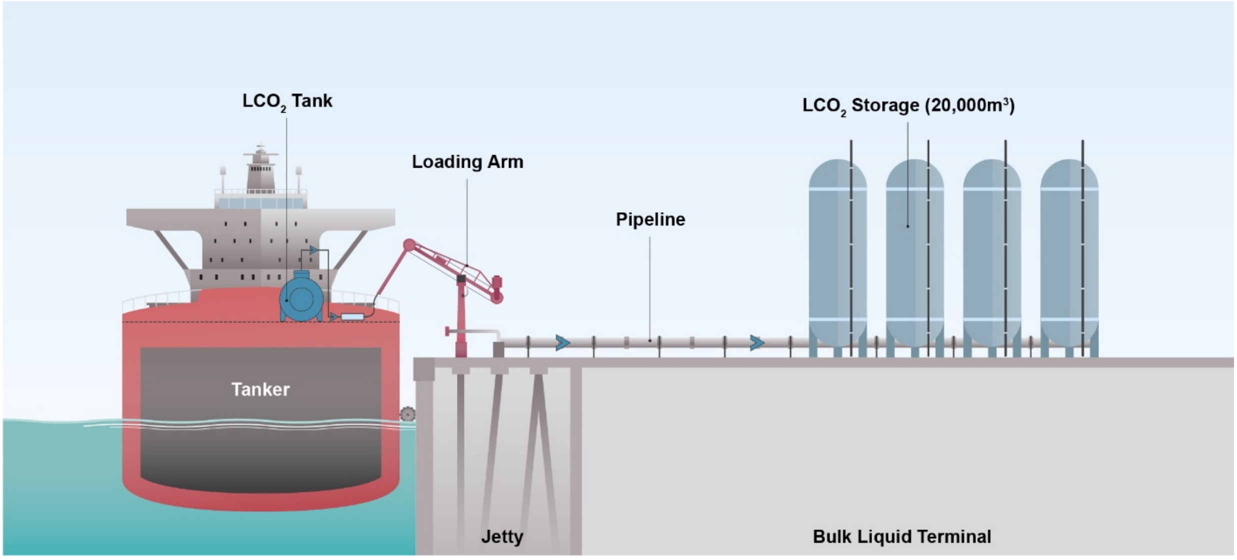


Figure 3.2 – Concept 1 – Ship-to-liquid bulk terminal

During offloading from the ship, the offloading pumps will be activated to pump LCO_2 continuously from the storage tank onboard the ship. The offloading pumps may be submersible pumps located inside the storage tank. A booster pump may also be required depending on the pressure profile of the downstream system. The on-board piping system with metering will then meet the interface of the onshore storage via an onshore Loading Arm /flexible hose. There will also be a metering system onshore between the loading arm and storage facility.

In the configuration where the LCO_2 is stored on the ship at MP, this pipeline will connect into the bulk liquid terminal storage tanks, which operate at LP. The pressure will be let down by a control valve before entry to the bulk terminal storage tanks. A heater may be required here to avoid freezing of contaminants, which will be considered at a later stage.

From the bulk liquid terminal storage tanks, a pump will connect to the vaporiser system which comprises a heater and knockout drum. During offloading, in order to maintain pressure in the LCO_2 storage tank onboard the ship, gaseous CO_2 will be transferred to the LCO_2 storage tank onboard the ship via a vapour return line. The vaporiser system will transfer the vaporised CO_2 through a vapor header, which also collects vapour that is boiling off the bulk liquid terminal storage tanks.

In the configuration where the ship storage is MP, the CO_2 from the liquid terminal storage tanks will be compressed from LP to MP. The recirculation line is attached to the ship with another flexible hose on the same loading arm the LCO_2 is offloaded from, and will transfer to the LCO_2 storage tank onboard ship.

The vaporiser system pressure is controlled using split-range pressure controllers, with signals feeding in from both ends of the header. This controls the flow valves to moderate the flow from the vapour header.

In the event the vapour header is not available, the PBU onboard the ship will be used to maintain pressure in the LCO_2 storage tank onboard ship. This consists of a heat exchanger which vaporises the LCO_2 in the on-board storage tank to increase pressure in the system as the vessel offloads. If the vapour header is connected and functioning correctly, the PBU will be inactive.

3.3.3 Concept 2 – Ship-to-Floating CO_2 Storage with Intermediate LCO_2 Receiving Vessel

Carbon capture units onboard ships will treat the flue gas to separate the CO_2. The CO_2 is liquefied and transferred into the LCO_2 storage tank onboard the ship, which is located above-deck for this concept. To manage boil-off from this tank, if needed there will be a Boil-Off Management System provided. This will function by a vapour line running from the top of the tank leading to a reliquefaction plant where the vapours will be reliquefied and returned to the LCO_2 storage tank in liquid form. Alternatively, storage tank insulation may provide sufficient endurance to handle the BOG for the design operating profile.

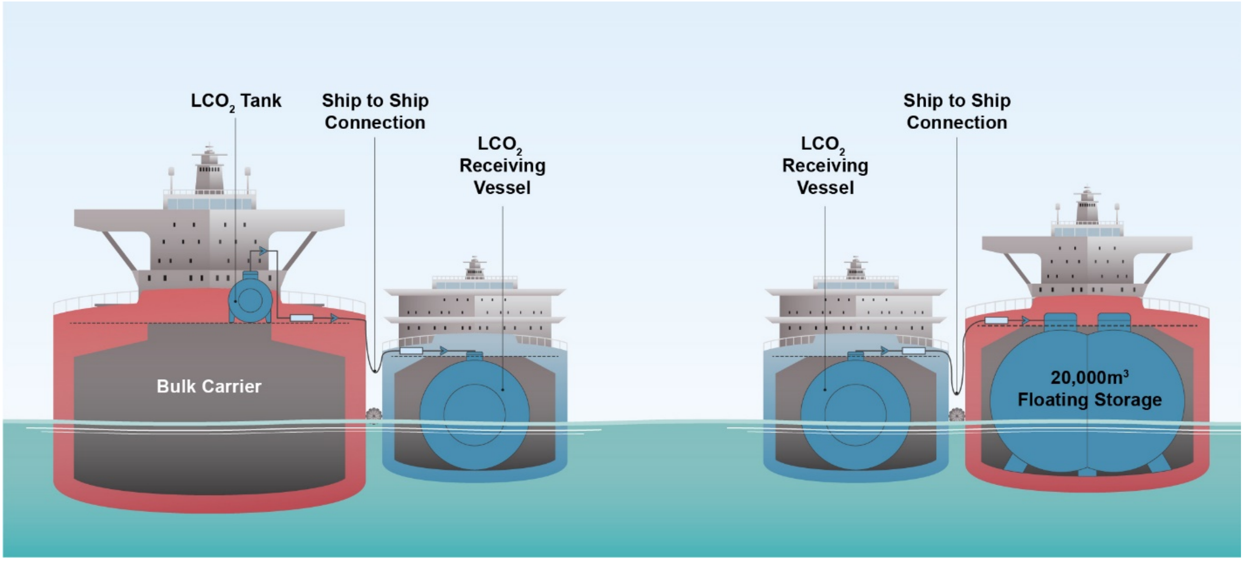


Figure 3.3 – Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel

During offloading from the ship, the offloading pumps will be activated to pump LCO_2 continuously out of the top of the storage tank onboard the ship. The offloading pumps may be submersible pumps located inside the storage tank. A booster pump may also be required depending on the pressure profile of the downstream system. The ship's pipeline with metering will then meet the interface of the intermediate LCO_2 receiving vessel, where there will be again a metering system and liquid transfer will take place with the aid of a loading arm which has a flexible hose, and located on the LCO_2 receiving vessel.

From the LCO_2 receiving vessel, a pump will connect to the vaporiser system which comprises of a heater and knockout drum. During ship offloading, in order to maintain pressure in the LCO_2 storage tank onboard the ship, gaseous CO_2 will be transferred to the LCO_2 storage tank onboard the ship. The vaporiser system will transfer the vaporised CO_2 into a vapour header, which also collects vapour that is boiling off the LCO_2 receiving vessels. In this header system, the vapour will pass through the recirculation line. To manage boil-off from LCO_2 receiving vessel there will be a refrigeration system onboard the LCO_2 receiving vessel. This will consist of two-phase compression, where vapour from LCO_2 receiving vessel will be compressed, before passing through a Flash Tank, before being compressed again and condensed, and returned into the flash tank.

In the configuration where the ship storage is MP, the CO_2 will be compressed from LP to MP. The recirculation line is attached to the ship with another flexible hose on the same loading arm the LCO_2 is offloaded through, to the LCO_2 storage tank onboard the ship. In the event the vapour header is not available, the PBU onboard the ship will be used to maintain pressure in the LCO_2 storage tank. This consists of a heat exchanger which vaporises the LCO_2 to increase pressure in the system as the vessel offloads. If the vapour header is connected and functioning correctly, the PBU will be inactive.

During discharging from the LCO_2 receiving vessel, the discharge pumps will be activated to continuously pump LCO_2 from the LCO_2 tanks of the intermediate receiving vessel. The discharge pumps may be submersible pumps located inside the cargo tanks. A booster pump may also be required depending on the pressure profile of the downstream system. The pipeline will then meet the interface of the floating CO_2 storage, where there will be a metering system and liquid transfer will take place with the aid of a loading arm which has a flexible hose. The loading arm will be located onboard the floating CO_2 storage. In the configuration, where the LCO_2 is stored on the receiving vessel at MP, this pipeline will then connect into the floating CO_2 storage tanks, which operate at LP. This pipeline will then connect into the tanks onboard the floating CO_2 storage vessel. From the tanks onboard the floating CO_2 storage vessel, a pump will connect to the vaporiser system which comprises of a heater and knockout drum.

During discharging, in order to maintain pressure in the LCO_2 receiving vessel, gaseous CO_2 will be transferred back to the LCO_2 receiving vessel. The vaporiser system will transfer the vaporised CO_2 into a vapour header, which also collects vapour that is boiling off the floating CO_2 storage tanks. In this header system, the vapour will pass through the recirculation line. In the configuration where the receiving vessel tanks are at MP, the CO_2 will be compressed from LP to MP. The recirculation line is attached to the LCO_2 receiving vessel with another flexible hose connected on the same Loading Arm the LCO_2 is offloaded through to the floating CO_2 storage.

The vaporiser system on the floating CO_2 storage is controlled using split-range pressure controllers, with signals feeding in from both ends of the header. This controls the flow valves to moderate the flow from the vapour header. In the event the vapour header is not available, the PBU onboard the LCO_2 receiving vessel will be used to maintain pressure. This consists of a heat exchanger which vaporises the LCO_2 to increase pressure in the system as the vessel offloads. If the vapour header is connected and functioning correctly, the PBU will be inactive.

3.3.4 Concept 3 – Ship-to-Liquid Bulk Terminal with Intermediate LCO_2 Receiving Vessel

Carbon capture units onboard ships will treat the flue gas to separate the CO_2. The CO_2 is liquefied and transferred into the LCO_2 storage tank onboard the ship, which is located below deck for this concept. To manage boil-off from this tank, if needed there will be a Boil-Off Management System provided. This will function by a vapour line running from the top of the tank leading to a reliquefaction plant where the vapours will be reliquefied and returned to the LCO_2 storage tank in liquid form. Alternatively, storage tank insulation may provide sufficient endurance to handle the BOG for the design operating profile.

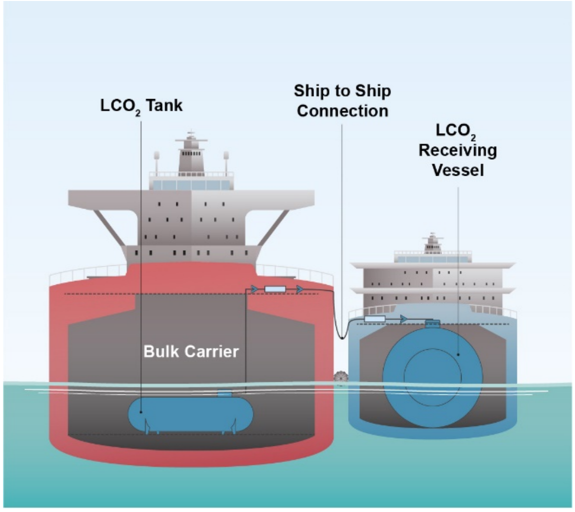


Figure 3.4 – Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel [stage 1]

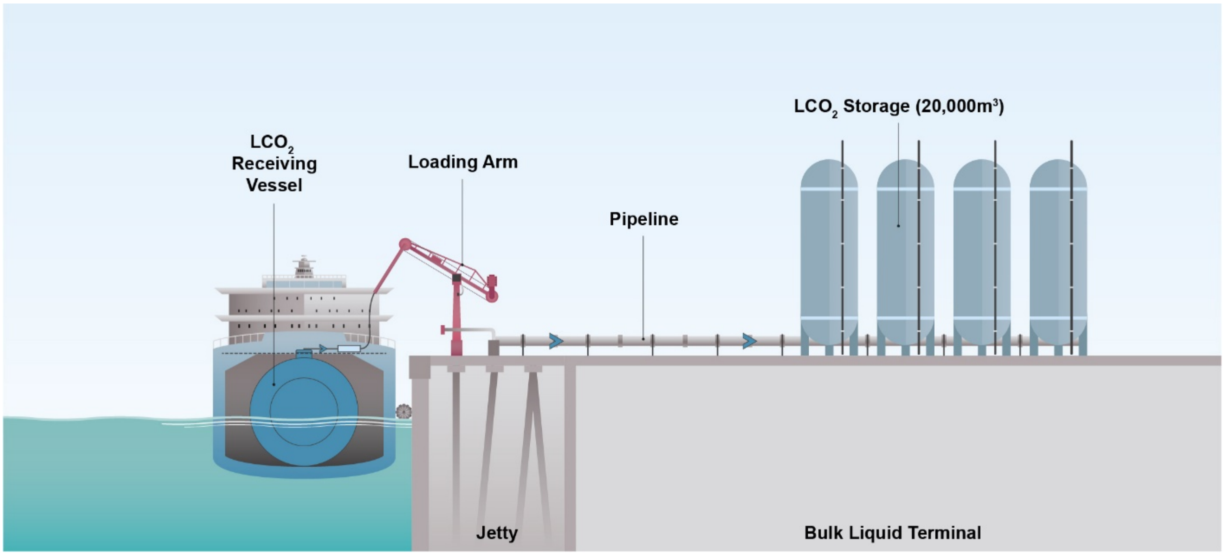


Figure 3.5 – Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel [stage 2]

During offloading of the ship, the offloading pumps will be activated to continuously pump LCO_2 from the storage tank onboard the ship. The offloading pumps may be submersible pumps located inside the storage tank. There may also be a booster pump here, if required. The onboard pipeline with metering will meet the interface of the intermediate storage onboard the LCO_2 receiving vessel, where there will be again a metering system and liquid transfer will take place with the aid of a loading arm or flexible hose, which will be located on the LCO_2 receiving vessel.

From the LCO_2 receiving vessel, a pump will connect to the vaporiser system which comprises of a heater and knockout drum. To manage boil-off from LCO_2 receiving vessel there will be a refrigeration system onboard the intermediate LCO_2 receiving vessel. This will consist of two-phase compression, where vapour from LCO_2 receiving vessel will be compressed, before passing through a Flash Tank, before being compressed again and condensed, and returned into the flash tank. During offloading, in order to maintain pressure in the LCO_2 storage tank onboard the ship, gaseous CO_2 will be transferred back to the

LCO_2 storage tank onboard the ship. The vaporiser system will transfer the vaporised CO_2 into a vapour header, which also collects vapour that is boiling off the LCO_2 receiving vessel tanks. In this header system, the vapour will pass through the recirculation line. In the configuration where the ship storage is MP, the CO_2 will be compressed from LP to MP. The recirculation line is attached to the ship with another flexible hose on the same loading arm the LCO_2 is offloaded through, to the LCO_2 storage tank onboard the ship. In the event the vapour header is not available, the PBU onboard the ship will be used to maintain pressure in the storage tank. This consists of a heat exchanger which vaporises the LCO_2 to increase pressure in the system as the vessel offloads. If the vapour header is connected and functioning correctly, the PBU will be inactive.

During discharging from the intermediate LCO_2 receiving vessel, the discharge pumps will be activated to continuously pump LCO_2 from the LCO_2 receiving vessel cargo tanks. The discharge pumps may be submersible pumps located inside the cargo tank. A booster pump may also be required depending on the pressure profile of the downstream system. The pipeline will then meet the interface of the onshore facilities, where there will be a metering system and liquid transfer will take place with the aid of a loading arm which has a flexible hose, which will be located onshore.

In the configuration where the LCO_2 is stored on the LCO_2 receiving vessel at MP, this pipeline will connect into the bulk liquid terminal storage tanks, which operate at LP. The pressure will be let down by a control valve before entry to the bulk terminal storage tanks. A heater may be required here to avoid freezing of contaminants, which will be considered at a later stage.

From the liquid bulk terminal storage tanks, a pump will connect to the vaporiser system which comprises a heater and knockout drum. During offloading, in order to maintain pressure in the LCO_2 receiving vessel, gaseous CO_2 will be transferred to the LCO_2 receiving vessel. The vaporiser system will transfer the vaporised CO_2 into a vapour header, which also collects vapour that is boiling off the liquid bulk terminal storage tanks. In this header system, the vapour will pass through the recirculation line. In the configuration where the LCO_2 receiving vessel cargo tanks are at MP, the CO_2 will be compressed from LP to MP. The recirculation line is attached to the ship with another flexible hose on the same loading arm the LCO_2 is discharge through, to the LCO_2 cargo tanks onboard the LCO_2 receiving vessel.

The vaporiser system located at the liquid bulk terminal is controlled using split-range pressure controllers, with signals feeding in from both ends of the header. This controls the flow valves to moderate the flow from the vapour header. In the event the vapour header is not available, the PBU onboard the intermediate LCO_2 receiving vessel will be used to maintain pressure. This consists of a heat exchanger which vaporises the LCO_2 to increase pressure in the system as the vessel discharges. If the vapour header is connected and functioning correctly, the PBU will be inactive.

3.3.5 Concept 4 – Ship-to-Terminal with ISO Tank Containers

Carbon capture units will be located on each container ship, where the flue gas will be treated to separate the CO_2 before it is liquefied and transferred to individual LCO_2 ISO tank containers via a manifold. These ISO tank containers are designed to store LCO_2 at appropriate temperature and pressure conditions with no boil-off management system. Each ISO tank container will have its own PRV directly venting into the atmosphere.

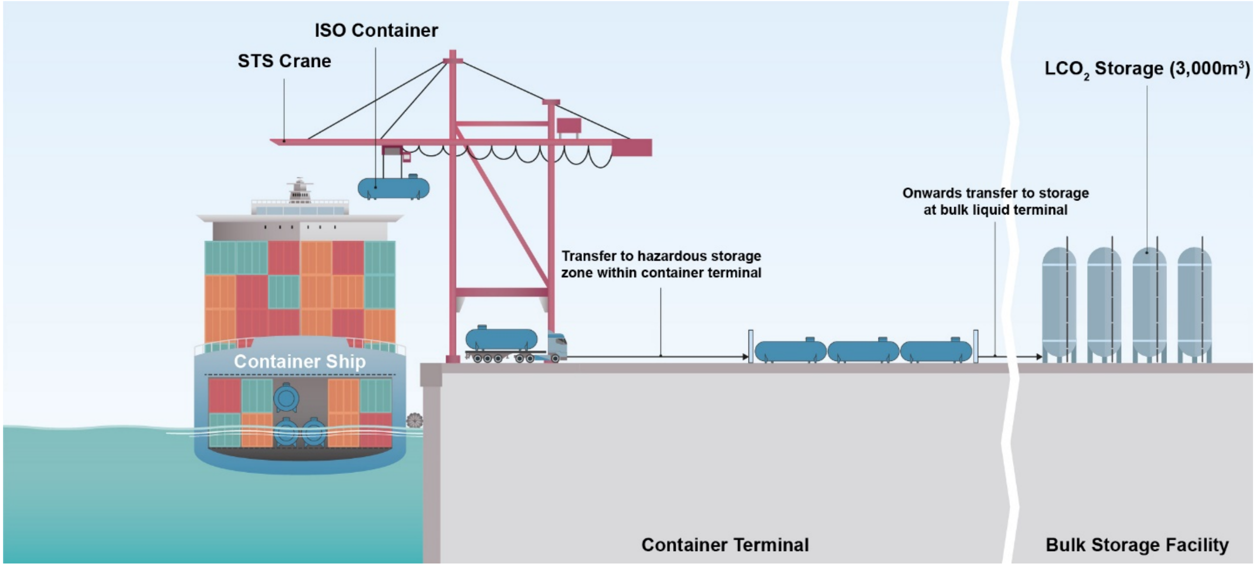


Figure 3.6 – Concept 4 – Ship-to-terminal with ISO tank containers

Filling of ISO tank containers from carbon capture unit will be stopped once the filling limit on the ISO container is reached as indicated by a level transmitter located on the ISO tank container. Once the container ship reaches the container terminal, ISO tank containers are to be lifted off from the container ship via an on-shore StS crane and placed on a truck, which will transport the containers to a hazardous storage zone located within the container terminal to ensure LCO_2 ISO tank containers are away from port operations. This mitigates risks of CO_2 leaks. Once at the hazardous storage zone, LCO_2 ISO tank containers will be transported to a bulk storage facility via truck.

At the bulk storage facility, LCO_2 ISO tank containers will be unloaded from truck via a flexible hose connection between ISO tank containers and fixed pipework at the bulk storage facility. During offloading of the LCO_2 ISO tank containers, pumps that are part of pumping facility at bulk storage terminal will be activated to pump LCO_2 from the bottom of the LCO_2 ISO tank containers to the top of the liquid bulk terminal storage tank. Alternatively, the ISO container / trailer truck may have PBU or transfer pump to transfer the LCO_2 to the bulk storage tanks. During offloading, in order to maintain pressure in LCO_2 ISO tank containers, a minimal amount of CO_2 will be pumped back to ISO tank containers.

3.4 References

[1] Nautic Expo, "Hyundai Ship Pump LNG," [Online]. Available: https://www.nauticexpo.com/prod/hyundai-marine-engines/product-32124-373850.html.

[2] Technip, "Flexible Pipe," [Online]. Available: https://www.technipfmc.com/media/45odl33w/flexible-pipe_210x270_web-2.pdf.

[3] Gutteling, "Ship to shore hoses," [Online]. Available: https://www.gutteling.com/products/hoses/ship-to-shore.

[4] "Marine loading arm Ship Engineering Bunkering," [Online]. Available: https://www.pngwing.com/en/free-png-mlvhi.

[5] Barber-Nichols, “LNG Vapor Return Compressors,” [Online]. Available: https://barber-nichols.com/products/compressors-fans/lng-vapor-return-compressors/.

[6] Equinor., “Northern Lights FEED Report,” [Online]. Available: https://norlights.com/what-we-do/reports.

[7] Krohne, “Custody transfer metering systems for LNG,” [Online]. Available: https://krohne.com/en/solutions/flow-metering-solutions/metering-systems/custody-transfer-metering-systems-lng.

[8] cryonorm, “Pressure Building Vaporizer,” [Online]. Available: https://cryonorm.com/air-gases/vaporizers/ambient-air-heated-vaporizer/pressure-building-vaporizer/.

[9] ASCO CO_2, “20' ISO-Tank-Container,” [Online]. Available: https://www.ascoCO_2.com/en/CO_2-and-dry-ice-equipment/CO_2-storage/20-iso-tank-container.

4. Design and Operation Standards for Offloading Liquid CO_2

4.1 Overview

This chapter delves into the current regulatory standards, mandatory guidelines, and recommended practices relevant to conceptualising arrangements for offloading liquefied carbon dioxide (LCO_2) from ships. It was observed that specific regulatory standards addressing LCO_2 offloading from ships are currently absent. However, existing standards governing the design, safety aspects of machinery, piping, and LCO_2 storage in other onshore industries, as well as standards in the LPG/LNG industry both onshore and aboard ships, bear similarities that could be adapted for LCO_2 offloading operations.

Historically and statistically, regulations tend to lag behind technological advancements. Developing the regulatory framework for LCO_2 offloading operations is expected to follow a similar pattern in terms of its conception and implementation.

Studying the existing regulatory framework and industry standards—directly through applicability or indirectly through adaptability—will offer insight and guidance to support future policy interventions that bridge the gap between maritime and onshore operations for LCO_2 offloading from ships.

Understanding the current regulatory landscape, standards, and both mandatory and recommended industry practices within maritime and onshore sectors will yield several benefits, including:

- Identifying regulatory gaps in LCO_2 offloading from ships.
- Anticipating barriers that could influence the development and requirements of LCO_2 offloading from ships.
- Providing guidance for stakeholders in crafting regulatory frameworks, standards, and guidelines to advance the regulation of LCO_2 offloading from ships.

4.2 Existing Standards and Guidelines

The arrangements on the vessels with OCCS and the arrangements ashore will have to take into account the requirements for the prospective transfer scenarios for offloading of LCO_2 including transfer to onshore storage terminal, StS transfer to a LCO_2 receiving vessel, ship-to-shore transfer of ISO tank containers (cassettes) and ship-to-floating CO_2 storage transfer.

The conceptualisation of the safe and efficient offloading of the captured CO_2 from storage arrangements on the ships to shore storage facilities requires a comprehensive study of not only the existing regulatory landscape that is pertinent to the process, but also relevant industry standards, guidelines and best practices that come into play from maritime as well as onshore perspective.

The study explored the existing standards pertaining to the onshore oil and gas industries where handling of CO_2 is at an established level that provides a firm knowledge base for the progression of OCCS.

Understanding the similarity that exists between the characteristics of LCO_2 and LPG/LNG, the knowledge base developed by the LPG and LNG industries which is adaptable to OCCS, the relevant standards have been considered. In addition, the standards and guidelines applicable to the LPG and LNG cargo vessels ship-to-shore transfers and ship-to-ship transfers have been considered and given the maturity of carriage of these commodities on ships they will form a vital knowledge base for the conceptualisation of the LCO_2 offloading arrangement on ships with OCCS.

Below tabulated regulatory standards, guidelines and best practices are the existing maritime and land-based requirements that are specific to the storage and offloading of CO_2, as well as those that address systems with properties that can be extrapolated to the process of offloading of CO_2.

The onboard captured LCO_2 offloading transfer arrangements have been classified into four categories (machinery, piping, storage and safety) where the standards, guidelines and recommended practices have been tabulated for each category to provide a clear distinction of their intent and in doing so enabling to clearly identify existing gaps that are perceived to currently exist in the safe and efficient offloading of LCO_2 from OCCS enabled ships.

- Machinery – Standards pertaining to equipment required for the storing and offloading systems including pumps, valves, temperature transmitters, pressure transmitters, flow transmitters and level transmitters.
- Piping – Standards pertaining to piping systems required to offload LCO_2 including stainless steel pipes and/or hoses.
- Storage – Standards pertaining to storage tanks required to store LCO_2 at required process conditions including storage tank material selection, storage tank safety systems and capacity sizing for bulk storage.
- Safety - Standards pertaining to the safe use and handling of LCO_2 across the whole OCCS chain and include design risks with operation of LCO_2 storage and offloading system as well as risk of handling LCO_2 during leak and/or phase change scenarios.

The standards, guidelines and recommended practices are tabulated separately as maritime standards and onshore standards with an 'Applicability' column describing relevance of each standard to the intent of the concept study to offload onboard captured carbon dioxide in Section 4.2.1 and 4.2.2.

A bird's eye view of the relevant standards applicable or adaptable to LCO_2 storage and offloading concepts is presented in Table 4.1 (Design) and Table 4.2 (Operation).

Table 4.1 – Summary coverage of existing design standards on LCO_2 storage and offloading (applicable or adaptable)

	Onboard Storage	Offloading		Terminal Storage
		Ship-to-Shore	Ship-to-Ship	
Design	• Class Society Rules and Regulations for the Classification of Ships • IMO IGC Code • IMO IGF Code • IMO IMDG Code • BCGA Code of Practice CP 26 • ISO 21028-2:2018 • ISO 20421-1:2019 • ISO 21013 – 1 & 2 • IMO IBC Code	• Class Society Rules and Regulations for the Classification of Ships • IMO IGC Code • IMO IGF Code • NACE TM0192-2003 • NACE TM 0297-2016 • DNV-RP-F104 • ISO 27913:2016 • BS EN 14161 • BS PD 8010 Part 1 • BS PD 8010 Part 2 • IP6 • ISO/TR 27912:2016 • ISO 17348:2016 • ASME B31.3 • CSA Z662-99 • ISO 13623:2017 • ISO 3183:2019 • ISO 3183-3:1999 • SIGTTO Recommendations and Guidelines for Linked Ship/Shore	• Class Society Rules and Regulations for the Classification of Ships • IMO IGC Code • IMO IGF Code • ISO 17438:2016 • ISO 21012:2018 • EN ISO 10380:2012 • EN 13765:2018 • ISO 2928:2021 • BS EN 13766:2010 • EN ISO 8031:2020 • BS EN 1762:2018 • EN 1474-2:2020 • BS 4089:1999 • ISO 20519:2017 • SIGTTO / OCIMF Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases • SIGTTO LNG Marine Loadings Arms and Manifold Draining, Purging and Disconnecting Procedure	• CGA G-6.1 • BCGA Code of Practice CP 26 • ISO 21028-2:2018 • ISO 20421-1:2019 • ISO 21013 – 1 & 2 • SIGTTO Information Paper Number 15 – A list of Design Guidelines for Liquefied Gas Terminal (referencing Ports and Jetties) • Pian MarCom WG172 • OCIMF Marine Terminal Information Booklet Guidelines and Recommendations

	Onboard Storage	Offloading		Terminal Storage
		Ship-to-Shore	Ship-to-Ship	
Design		Emergency Shutdown of Liquefied Gas Cargo Transfer System 2021 • SIGTTO LNG Marine Loadings Arms and Manifold Draining, Purging and Disconnecting Procedure • ISO 28460:2010 • SIGTTO / OCIMF Recommendations for Liquefied Gas Carrier Manifolds • Pianc MarCom WG33 - Guidelines for the design of fender systems • OCIMF – Mooring Load Analysis / MEG Guidelines • SIGTTO - Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquefied Gas Transfer Systems, 2018 • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships	• SIGTTO / OCIMF Recommendations for Liquefied Gas Carrier Manifolds • OCIMF – Mooring Load Analysis / MEG Guidelines • SIGTTO - Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquefied Gas Transfer Systems, 2018 • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships	

Notes: ASME - American Society of Mechanical Engineers, BCGA - British Compressed Gases Association, BS - British Standards, CGA - Compressed Gas Association, CSA - Canadian Standards Association, DNV - Det Norske Veritas, IBC - Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk, IGF – International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels, IMDG - International Code for the Maritime

Transport of Dangerous Goods, NACE - National Association of Corrosion Engineers, OCIMF - Oil Companies International Marine Forum, SIGTTO - Society of International Gas Tanker and Terminal Operators

Table 4.2 – Summary coverage of existing operation standards on LCO_2 storage and offloading (applicable or adaptable)

	Onboard Storage	Offloading		Terminal Storage
		Ship-to-Shore	Ship-to-Ship	
	• BCGA Code of Practice CP 26 • ISO 27913:2016 • ISO 17349:2016 • ISO 20421-2:2017 • API 521 • IMO IGC Code • IMO IGF Code • ISO 23269-1 : 2008 - Ships and marine technology - Breathing apparatus for ships - Part 1: Emergency escape breathing devices (EEBD) for shipboard use	• DNV OS-F101 • ISO 17349:2016 • CSA Z662-99 • ISO 13623:2017 • IMO IGC Code • IMO IGF Code • SIGTTO Recommendations and Guidelines for Linked Ship/Shore Emergency Shutdown of Liquefied Gas Cargo Transfer System 2021 • SIGTTO LNG Marine Loadings Arms and Manifold Draining, Purging and Disconnecting Procedure • ISO 28460:2010 • IMO London Convention as amended by Protocol of 1996 • OCIMF / CCNR - International Safety Guide for Inland Navigation	• ISO 17349:2016 • EN ISO 10380:2012 • BS 4089:1999 • IMO IGC Code • IMO IGF Code • OCIMF Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases 2013 • ISO 20519:2017 • SIGTTO / OCIMF Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases • OCIMF / CCNR - International Safety Guide for Inland Navigation Tank-Barges and Terminals (ISGINTT) • IMO MARPOL	• ISO/TR 27915:2017 • BCGA Code of Practice CP 26 • ISO 27913:2016 • ISO 17349:2016 • IGC Doc 119/04/E • ISO 20421-2:2017 • API 521 • IMO IGC Code • SIGTTO Information Paper Number 15 – A list of Design Guidelines for Liquefied Gas Terminal (referencing Ports and Jetties) • Pianc MarCom WG172

	Onboard Storage	Offloading		Terminal Storage
		Ship-to-Shore	Ship-to-Ship	
Operation		Tank-Barges and Terminals (ISGINTT) • IMO MARPOL • IMO MEPC 376(80) - Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines) • SIGTTO - LPG Shipping Suggested Competency Standards • SIGTTO - Liquefied Gas Handling Principles on Ships and in Terminals, (LGHP4), 2016 • ISO 28460:2010 - Ship-to-shore interface and port operations • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships • ISO 23269-1 : 2008 - Ships and marine technology - Breathing apparatus for ships - Part 1: Emergency escape breathing devices (EEBD) for shipboard use	• IMO MEPC 376(80) - Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines) • SIGTTO - LPG Shipping Suggested Competency Standards • SIGTTO - Liquefied Gas Handling Principles on Ships and in Terminals, (LGHP4), 2016 • ISO 28460:2010 - Ship-to-shore interface and port operations • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships • ISO 20519:2017 - Ships and marine technology - Specification for bunkering of gas fuelled ships • ISO 23269-1 : 2008 - Ships and marine technology - Breathing apparatus for ships - Part 1: Emergency escape breathing devices (EEBD) for shipboard use	• OCIMF Marine Terminal Information Booklet Guidelines and Recommendations • SIGTTO - Guide to Contingency Planning for Marine Terminals Handling Liquefied Gases in Bulk, 2001

Notes: API - American Petroleum Institute, EEBD - Emergency escape breathing devices, ISGINTT - International Safety Guide for Inland Navigation Tank-Barges and Terminals, MARPOL - International Convention for the Prevention of Pollution from Ships

4.2.1 Maritime Standards

4.2.1.1 Maritime – Machinery Standards

Standards	Title	Description	Applicability
Classification Society Rules	Rules and Regulations for the Classification of Ships	Various class societies have published rules and guidance for OCCS. The rules set out the requirements for general arrangements, machinery, electrical, control & safety systems, containment systems and piping systems for OCCS on ships. Ships that comply with the requirements are awarded with a class notation or similar. Ships that are designed for future installation of OCCS are also awarded with a "ready" notation or similar.	The rules are applicable to the design of the machinery and associated electrical, control and safety systems of the LCO_2 offloading arrangement onboard ships.
IMO IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk	The code applies to ships regardless of their sizes, including those of less than 500 gross tonnages, engaged in carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C, and certain other substances listed in chapter 19 of the Code. It also provides guidelines on the transfer of liquefied gases from ship-to-ship and ship-to-shore.	The code in prescribing the design and construction standards of ships involved in liquefied gases in bulk is applicable to LCO_2 storage and transfer systems onboard vessels in its emphasis on safety systems such as alarm systems, safety equipment, and the need for safety procedures, outlines recommended operating practices and procedures for loading, unloading, and cargo handling.

Standards	Title	Description	Applicability
IMO IGF Code	International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels	The code provides mandatory criteria for the arrangements and installation of machinery, equipment and systems for vessels operating with gas or low-flashpoint liquids as fuel to minimise the risk to ship, its crew and the environment.	The applicability of the code is through adaptability of its requirements of handling gas fuels like LNG that share similarities with LCO_2 and will provide useful insights in the conceptualisation of the arrangements for LCO_2 offloading to minimise the risk to ship, its crew and environment.
IMO IBC Code	Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk	The code prescribes the design and construction standards of ships and the equipment they should carry, with due regard to the nature of the products involved and to minimise the risks to ships, their crews and the environment.	The code may be used as guidance for transportation of Mono-ethanolamine (MEA) as solvent for use in the OCCS. However, this is outside the scope of the study of offloading of onboard captured carbon dioxide.
SIGTTO	Recommendations for Valves on Liquefied Gas Carriers, 2023	The guidelines provide guidance to designers and operators on the general requirements for valves on all gas carriers including LPG and LNG carriers. In the document, the term LPG refers to liquefied gas cargoes carried between the temperature range of 0°C to –104°C, so including the use of LCO_2.	Applicable to LCO_2 systems given that LCO_2 and LPG are both substances handled and stored under pressure in liquefied form. Specifically, guidelines in selecting valves according to pressure and temperature of LCO_2, material compatibility, required flow rate and safety features of the valve as well as testing of valves before their installation i.e., pressure, leak and operational testing.

4.2.1.2 Maritime – Piping Standards

Standards	Title	Description	Applicability
Classification Society Rules	Rules and Regulations for the Classification of Ships	Various class societies have published rules and guidance for OCCS. The rules set out the requirements for general arrangements, machinery, electrical, control & safety systems, containment systems and piping systems for OCCS on ships.	The rules are applicable to the design of the piping systems and associated components for the LCO_2 offloading arrangement onboard ships.
IMO London Convention as amended	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 as amended by Protocol of 1996	The purpose of the London Convention is to control all sources of marine pollution and prevent pollution of the sea through regulation of dumping into the sea of waste. The protocol to the convention sets compliance procedures and mechanisms to ensure compliance.	Relevant to disposal of captured CO_2 under seabed and it is expected that the cross-country transport of LCO_2 will be governed under this legislation.
CDI / ICS / OCIMF / SIGTTO	Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases 2013	The guidelines provide advice for Masters, Marine Superintendents and others, such as StS service providers and transfer organisers, involved in the planning and execution of StS operations.	Applicable to assessing and managing risks associated with handling LCO_2 during StS transfer process, compatibility of design between different vessel types and offloading setups (fittings, hoses, transfer systems) and operational procedures (pre-transfer checklist, during transfer monitoring and control to post-transfer procedures)
SIGTTO / OCIMF	Recommendations for Liquefied Gas Carrier Manifolds, 2018	The guidelines provide recommendations on the layout, strength and fittings for gas carrier manifolds. It is applicable to both LPG and LNG carriers.	The recommendations are not explicitly designed for LCO_2, but they can provide useful principles that could be applied in this context. They provide specific guidance on how the manifolds should be arranged, how many should be present, and how they should be configured for safe and efficient transfer, safety considerations for LNG and LPG transfers that are also relevant for LCO_2 transfers and recommendations on the

Standards	Title	Description	Applicability
			design of the ship's manifold compatible with the design of the terminal manifold.
OCIMF / CCNR	International Safety Guide for Inland Navigation Tank-Barges and Terminals (ISGINTT)	The guidelines provide recommendations for inland tanker and terminal personnel on the safe carriage and handling of liquid inland tanker cargoes including petroleum, chemicals or liquefied gas inland tankers, as well as the terminals handling those inland tankers.	The applicability of the guidance is in the operational advice to assist personnel directly involved in the offloading LCO_2 from ships through interface of inland tank-barge.
SIGTTO	LNG Marine Loadings Arms and Manifold Draining, Purging and Disconnecting Procedure	The guidelines provide advice specifically pertains to terminals employing rigid marine loading arms (MLAs). The basic principles are applicable for hose systems that may be used for ship-to-ship transfer as well, but there will be differences in the details for LCO_2 transfer.	Principles and procedures regarding manifold draining, purging and disconnection could be adapted to the off-loading of LCO_2 captured onboard ships.

4.2.1.1 Maritime – Storage Standards

Standards	Title	Description	Applicability
Classification Society Rules	Rules and Regulations for the Classification of Ships	Various class societies have published rules and guidance for OCCS. The rules set out the requirements for general arrangements, machinery, electrical, control & safety systems, containment systems and piping systems for OCCS on ships.	The rules are applicable to the design of storage systems and associated components for the LCO_2 offloading arrangement onboard ships.
IMO IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk	The code applies to ships regardless of their size, including those of less than 500 gross tonnages, engaged in carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C, and certain other substances listed in chapter 19 of the Code. It also provides guidelines on the transfer of liquefied gases from ship-to-ship and ship-to-shore.	The code provides standard for construction of Type C independent tanks which can be adapted for LCO_2 storage tank onboard ships.

Standards	Title	Description	Applicability
IMO IMDG Code	The International Maritime Dangerous Goods Code	The code sets out requirements for the maritime transport of dangerous goods in packaged form in order to harmonize the safe carriage of dangerous goods and to prevent pollution.	Applicable to the storage and offloading of LCO_2 in packaged form (ISO tank containers).
IMO MEPC.376(80)	Guidelines on life cycle GHG intensity of marine fuels (LCA Guidelines)	The guidelines provide guidance on lifecycle GHG intensity assessment for all fuels and other energy carriers used on-board a ship.	The LCA Guidelines were adopted in MEPC 80th session and set out methods to calculate Well-to-Tank and Tank-to-Wake GHG emissions for marine fuels. The MEPC 80 in further development of the LCA guidelines considered initiating a work process on the aspect of OCCS and postponed the discussion on the subject matter to the ISWG on GHG reductions meeting prior MEPC 81 in March 2024.

4.2.1.2 Maritime – Safety Standards

Standards	Title	Description	Applicability
Classification Society Rules	Rules and Regulations for the Classification of Ships	Various class societies have published rules and guidance for OCCS. The rules set out the requirements for general arrangements, machinery, electrical, control & safety systems, containment systems and piping systems for OCCS on ships.	The rules are applicable to accounting for the safety aspects associated with LCO_2 offloading arrangement onboard ships and provide for risk based certification where the risk assessments may identify required design changes to equipment, components, arrangements and safeguards to meet an agreed risk criteria for which prescriptive standards are not available.
IMO SOLAS	International Convention for the Safety of Life at Sea, 1974	The convention specifies minimum standards for the construction, equipment and operation of ships, compatible with their safety	The construction of the vessel and of its equipment, and operation of these equipment including the OCCS will have to consider the

Standards	Title	Description	Applicability
			requirements of the relevant provisions within SOLAS.
IMO MARPOL	International Convention for the Prevention of Pollution from Ships	The convention specifies the requirements for prevention of pollution of the marine environment by ships with Annex VI of the convention addressing requirements for air pollution prevention from ships.	The convention does not currently include CO_2 captured onboard a ship as a waste product, although it addresses air pollution through Annex VI. It is expected that IMO will be addressing regulatory aspects of offloading captured CO_2 within the convention in the future.
IMO STCW Convention	International Convention on Standards of Training, Certification & Watch keeping for Seafarers	The Convention prescribes minimum standards relating to training, certification and watchkeeping for seafarers.	The applicability of the convention and the associated code is towards the establishment of standards for training and training for onboard personnel towards the competence elements that will be involved in the safe offloading of LCO_2.
IMO ISPS Code	International Ship and Port Facility Security Code	The code outlines detailed maritime and port security-related requirements which SOLAS contracting governments, port authorities and shipping companies must adhere to, in order to be in compliance with the Code and provides a series of recommendatory guidelines to meet the requirements and obligations.	The relevance of the code is towards the assessment of the component of security risk (if any) that the offloading of LCO_2 and in extension the presence of LCO_2 onboard the ships brings in from the security context of the ships and port facilities.
Pianc MarCom WG33	Guidelines for the design of fender systems	The guidelines provide guidance on types of fenders, fendering systems and layouts, mooring devices and ropes, mooring system layouts for commercial vessels, and recommendations as to their suitability for various applications and locations.	Applicable to mooring of vessels at berth when offloading LCO_2.
Pianc MarCom WG121	Harbour Approach Channels - Design Guidelines	The guidelines provide recommendations for the design of vertical and horizontal dimensions of harbour	Applicable when determining dredge depths at berth and navigational approach, and any

Standards	Title	Description	Applicability
		approach channels and the manoeuvring and anchorage areas within harbours, along with defining restrictions to operations within a channel.	specific considerations that may be taken into account relevant to LCO_2 offloading.
Pianc MarCom WG172	Guidelines for the Design of Small- to Mid-Scale Marine LNG Terminals Including Bunkering	The guidelines provide design guidance for small to mid-scale LNG fixed terminals including LNG bunkering for designers and operators of marine LNG terminals and infrastructure.	Applicability through adaptation of the common elements of LNG terminal infrastructure to LCO_2 storage infrastructure at terminals.
OCIMF	Mooring Load Analysis during Ship-to-Ship Transfer Operations	The guidelines provide support to stakeholders in making their own assessments to determine suitable weather criteria and ascertain an appropriate weather window for STS operations.	Applicable to assessment of weather-related risks for mooring during ship-to-ship transfer of LCO_2.
OCIMF	Mooring Equipment Guidelines (MEG4), 2018	The guidelines provide recommended minimum requirements that will help ship designers, terminal designers, ship operators and mooring line manufacturers improve the design, performance, and safety of mooring systems.	MEG4 guidelines could be used to ensure that the ships involved in CO_2 offloading are moored safely during the process, provide guidelines for ship-to-ship operations, which could be applied to ensure safe transfer of LCO_2 between vessels.
SIGTTO	Recommendations for Emergency Shutdown and Related Safety Systems 2021	The guidelines provide are presented for the installation of a standardised electrical link that connects ship and terminal emergency shutdown systems, so that in case of a potential hazard, an emergency shutdown of liquefied gas cargo transfer can be initiated rapidly and safely.	The guidance in particularly relevant to emergency shutdown and related safety systems for liquefied gas cargo transfers and the safety elements can well be adapted to offloading of captured LCO_2.
SIGTTO	Guidance on Gas Carriers and Terminal Gangway Interface	The guidelines provide information on design considerations for the gangway landing areas on ships and the gangway system for terminals and discusses different gangway types and configurations and provides	Applicable as it provides guidance for safe access to the ship fitted with OCCS via the gangway during LCO_2 offloading.

Standards	Title	Description	Applicability
		recommendations in an effort to maximise safe access to the ship via the gangway.	
SIGTTO	Guidelines for the Alleviation of Excessive Surge Pressures on ESD for Liquefied Gas Transfer Systems, 2018	The guidance explains the concept of surge pressure and provides practical advice on its associated hazards and risk management. It outlines the principal design and operational recommendations for cargo transfer systems for the benefit managers, designers, and operators of liquefied gas carriers.	The guidance is relevant for the mitigation of surge pressure hazards by the incorporation of ESD system including those associated with the sudden cessation of CO_2 transfer operations.
SIGTTO	LPG Shipping Suggested Competency Standards	The guidelines provide guidance for organisations involved in training officers, including cargo engineers, for LPG cargo operations.	Applicable as standards provide guidelines for training and certification of seafarers working on LPG that can be useful when considering application of such guidelines to OCCS. Specifically, they provide guidelines on procedures and safety measures for loading and offloading LPG which can be applied to LCO_2 and training seafarers on use and maintenance of equipment used in OCCS and offloading of LCO_2.
SIGTTO	Liquefied Gas Handling Principles on Ships and in Terminals, (LGHP4), 2016	The guidelines provide guidance to cover every aspect of the safe handling of bulk liquid gases (LNG, LPG, and chemical gases) onboard ships and at the ship/shore interface at terminals, and emphasise the importance of understanding physical properties of gases in relation to the practical operation of gas-handling equipment on ships and at terminals.	Specify a set of principles for the handling of liquefied gases on ships and in terminals. These principles address a wide range of considerations from safety, operational and technical perspectives. While these principles are typically used for liquefied gas carriers and associated terminal operations, they are adaptable to design of offloading systems of LCO_2.
SIGTTO	Guide to Contingency Planning for Marine Terminals Handling Liquefied Gases in Bulk, 2001	The guidelines provide guidance to safe storage and transfer of liquefied gases at marine terminals. It can be adapted for use at any terminal that handles hazardous substances in bulk. Provide guidance on contingency	Principles laid out can be applied to assess risks and develop contingency plans for LCO_2 offloading, for example hazards associated with the offloading process, design and operation of

Standards	Title	Description	Applicability
		planning, including identification and control of potential hazards, control of incidents and review periods.	offloading systems and training and competence of personnel involved. They also provide considerations for the design of terminals and equipment used for handling of liquefied gases.
ISO 28460:2010	Ship-to-shore interface and port operations	The standard specifies the requirements for ship, terminal, and port service providers to ensure the safe transit of an LNG carrier through the port area and the safe and efficient transfer of its cargo. It is applicable to pilotage and Vessel Traffic Services (VTS); tug and mooring boat operators; terminal operators; ship operators; suppliers of bunkers, lubricants and stores and other providers of services whilst the LNG carrier is moored alongside the terminal.	LNG shares similar properties with LCO_2 under consideration (LP and MP options) in terms of temperatures, albeit much higher temperatures than LNG which makes the handling characteristics transferable to the offloading of LCO_2.
ISO 20519:2017	Ships and marine technology - Specification for bunkering of gas fuelled ships	The standard provides guidance on specification for bunkering of gas fuelled ships.	Applicable to LNG bunkering and elements of which can be adapted for LCO_2 offloading.
ISO 23269-1 : 2008	Ships and marine technology - Breathing apparatus for ships - Part 1: Emergency escape breathing devices (EEBD) for shipboard use	The standard provides performance specifications for (EEBD required by regulation in Part D of chapter II-2 of the 1974 International Convention for the Safety of Life at Sea (SOLAS), as amended in 2000, and chapter 3 of the IMO International Code for Fire Safety Systems (FSS Code) and are devices intended to supply air or oxygen needed to escape from accommodation and machinery spaces with a hazardous atmosphere.	Applicable to LCO_2 storage and offloading systems onboard ships where means to escape from spaces susceptible to LCO_2 leakage.

4.2.2 Onshore Standards

4.2.2.1 Onshore – Machinery Standards

Standards	Title	Description	Applicability
NACE TM0192-2003	Evaluating Elastomeric Materials in Carbon Dioxide Decompression Environments.	The standard provides procedures to measure the effect on elastomeric materials subjected to rapid depressurisation from elevated pressures in dry carbon dioxide environments and is designed for testing O-rings or other specimens of elastomeric vulcanites.	Relevant for assessing and selection of the materials used in the construction of the OCCS including the arrangements of offloading of LCO_2 under various pressure conditions. The standard could help guide decisions in the selection of elastomeric about the best materials to use to ensure the safe and efficient operation of the system.
NACE TM 0297-2016	Effects of High-Temperature, High-Pressure Carbon Dioxide Decompression in Elastomeric Materials	The standard provides information on CO_2 environment testing at pressures greater than atmospheric pressure and temperatures of 50°C (122°F) or greater. It is intended to serve as a tool in the evaluation of elastomeric materials for use in the oil field and other energy-related areas where CO_2 gaseous environments are encountered.	Relevant for assessing and selection the materials used in the construction of the OCCS including the arrangements of offloading of LCO_2 under various temperature conditions. The standard could help guide decisions in the selection of elastomeric about the best materials to use to ensure the safe and efficient operation of the system, especially in high pressure CO_2 environments.
ISO/TR 27912:2016	Carbon dioxide capture — Carbon dioxide capture system, technologies and processes	The technical report provides guidance principles and information necessary for the development of standards for CO_2 capture part of the CCS chain, and also covers technologies, equipment and processes specific to CO_2	The applicability of the guidance is in the information on the quality of the captured CO_2 as the allowable purity of the offloaded LCO_2 will be dependent on the pipeline transportation

Standards	Title	Description	Applicability
		capture from the viewpoints of the international standardisation for the implementation of CCS.	limitations as well as its end use being either geologic storage, enhanced oil recovery (EOR), food-grade applications or feedstock for chemical production.
IEC/PAS 80005-3:2014	Utility connections in port - Part 3: Low Voltage Shore Connection (LVSC) Systems - General requirements	The standard specifies the requirements that support standardisation of connection between compliant ships and compliant low voltage shore power supplies though a compliant LVSC system at different berths.	The applicability of the standard to LCO_2 offloading is in the standardisation and availability of compliant LVSC systems including compatible ESD devices, and other scenarios where low voltage shore power may need to be connected to the vessel.

4.2.2.2 Onshore – Piping Standards

Standards	Title	Description	Applicability
DNV-RP-F104	Design and operation of carbon dioxide pipelines	The Recommended Practice (RP) provides guidance for the design, construction, and operation of CO_2 pipelines, related to structural integrity. The document supplements requirements in the referenced pipeline standards.	Primarily intended for CO_2 pipelines, several aspects of the RP are relevant to the design of LCO_2 offloading systems for maritime applications. This standard provides detailed specifications for materials and design considerations that can be used for the offloading system, operational safety during the transportation of LCO_2 , includes guidelines for risk assessment of CO_2 pipelines which could be adapted to the risks associated with offloading LCO_2 from ships, specifications for the quality and properties of

Standards	Title	Description	Applicability
			LCO_2 that is to be transported which aids in determining required properties of LCO_2 that is to be offloaded from ships.
ISO 27913:2016	Carbon dioxide capture, transportation, and geological storage - Pipeline transportation systems	The standard specifies additional requirements and recommendations not covered in existing pipeline standards for the transportation of CO_2 streams from the capture site to the storage facility where it is primarily stored in a geological formation or used for other purposes (e.g., EOR or CO_2 use).	The applicability of the standard with respect to the LCO_2 offloading arrangements is the emphasis on requirements towards quality assurance of the CO_2 stream, and on health, safety and environment aspects of CO_2 in gaseous as well as in liquid phase.
BS EN 14161	Petroleum and Natural Gas Industries - Pipeline Transportation Systems	The standard applicable to rigid metallic pipelines specifies requirements and gives recommendations for the design, materials, construction, testing, operation, maintenance, and abandonment of pipeline systems used for transportation in the petroleum and natural gas industries.	Provides principles and guidelines that may be useful for the design, fabrication, installation, and testing of pipeline systems used in the transfer of LCO_2. These include selection of materials, wall thickness, design pressure and temperature; guidelines for pipeline construction, including welding, inspection, and testing procedures and development of operational and maintenance protocols for the LCO_2 offloading process, ensuring safety and efficiency.
BS PD 8010 Part 1	Code of practice for pipelines -Steel pipelines on land	The code provides recommendations for and guidance on the design, selection, specification and use of materials, routeing, land acquisition, construction, installation, testing, operation, maintenance, and abandonment of land pipeline systems constructed from steel.	Pipelines designed to BS EN 14161 should be supported by good industry practice as presented in BS PD 8010 Parts 1 and 2. Part 1 of the code is applicable to steel pipelines intended for the conveyance of liquids and gases including LCO_2 offloading arrangements on land.
BS PD 8010 Part 2	Code of practice for pipelines - Subsea pipelines	The code gives recommendations for and guidance on the design, selection, specification and use of materials, construction, installation, testing,	Pipelines designed to BS EN 14161 should be supported by good industry practice as presented in BS PD 8010 Parts 1 and 2. Part 2 of the code of

Standards	Title	Description	Applicability
		commissioning, operation, maintenance, and abandonment of steel subsea pipelines in offshore, nearshore and landfall environments.	practice is applicable to subsea pipelines intended for the conveyance of liquids and gases including LCO_2.
DNV OS-F101	Submarine Pipeline Systems	The guidance provides requirements and recommendations for the concept development, design, construction, operation, and abandonment of pipeline systems, with the emphasis on structural integrity.	Principles can be applied to piping systems needed for the offloading of LCO_2 from ships. These include considerations for pipeline thickness, strength, and corrosion resistance and construction and validation of the systems for offloading LCO_2.
IP6	Institute of Petroleum Pipeline Code IP6	The code provides guidance on pipeline codes applicable to oil & gas industries and considerations employed for pipelines.	IP6 is still in existence but is not widely used for new pipelines. It does contain useful guidance on operational issues that may be applicable to LCO_2 offloading arrangements.
ISO 17348:2016	Petroleum and natural gas industries — Materials selection for high content CO_2 for casing, tubing and downhole equipment	The standard provides guidelines and requirements of material selection of seamless casing and tubing, and downhole equipment for CO_2 with high pressure and high CO_2 content environments [higher than 10 % (molar) of CO_2 and 1 MPa CO_2 partial pressure].	The applicability of the standard is in the guidance provided on CO_2 towards corrosion evaluation, material selection and corrosion control.
ISO/TR 27915:2017	Carbon dioxide capture, transportation and geological storage — Quantification and verification	The technical report covers all components of the CCS chain including capture, transport and storage, and includes a lifecycle assessment approach to estimate project level emissions and emission reductions from project assessment, construction and operations, through to completion and post-closure activities.	The applicability of the guidance is in the insights provided on the composition of the CO_2 stream, including its purity, and requirements for measuring and verifying the physical and chemical state of the CO_2 stream.

Standards	Title	Description	Applicability
ISO 20088-1:2016	Determination of the resistance to cryogenic spillage of insulation materials — Part 1: Liquid phase	The standard describes a method for determining the resistance to liquid cryogenic spillage on cryogenic spillage protection (CSP) systems.	The applicability is in the assessment of resistance towards exposure of LCO_2 on the insulation materials installed on carbon steel and have a possibility of contact with LCO_2 in case of a spillage.
ASME B31.3	Process Piping	The standard contains requirements for piping typically found in petroleum refineries; onshore and offshore petroleum and natural gas production facilities; chemical, pharmaceutical, textile, paper, ore processing, semiconductor and cryogenic plants; food and beverage processing facilities; and related processing plants and terminals.	ASME B31.3 provides detailed rules for the design of piping systems and their components. This includes stress calculations for pressure containment, considerations for thermal expansion, and factors to be considered for different loading conditions. It will influence the design of the onboard captured CO_2 offloading process, including the piping systems connecting the storage areas on the ships to the offloading points, as well as any piping necessary for the transfer to different receptacles. Standard also specifies acceptable materials for different types of fluids and conditions. The materials of construction for the piping, valves, pumps, and other components involved in the LCO_2 offloading process would need to be chosen based on these requirements.
CSA Z662-99	Oil and Gas Pipeline Systems	The standard covers the design, construction, operation, and maintenance of oil and gas industry pipeline systems that convey liquid hydrocarbons (including crude oil, multiphase fluids, condensate, liquid petroleum products, natural gas liquids, and liquefied petroleum gas), oilfield water; oilfield steam, carbon dioxide used in oilfield enhanced recovery schemes or gas.	Relevant if the captured CO_2 is to be transported via pipelines at any point during the offloading process. Provide guidance on the design and construction of pipelines that could be used for the transportation of LCO_2 from the ship to the shore, or from the ship to another vessel, procedures for the safe operation and maintenance of pipelines, guidance on safety management and environmental protection.

Standards	Title	Description	Applicability
ISO 13623:2017	Petroleum and natural gas industries - Pipeline transportation systems	The standard specifies requirements and gives recommendations for the design, materials, construction, testing, operation, maintenance, and abandonment of pipeline systems used for transportation in the petroleum and natural gas industries. It applies to pipeline systems on-land and offshore, connecting wells, production plants, process plants, refineries and storage facilities, including any section of a pipeline constructed within the boundaries of such facilities for the purpose of its connection.	Guides the design and material selection for the transportation of captured CO_2 from the ship to different receptacles, ensuring safety, durability, and efficiency. This would be particularly relevant for pipeline systems facilitating ship-to-ship, ship-to-shore, and ship-to-floating storage transfers of CO_2. Could also be used in the construction and testing of the proposed CO_2 offloading systems, inform the operation and maintenance of the CO_2 offloading systems, potentially increasing their longevity, and reducing the risk of system failures.
ISO 3183:2019	Petroleum and natural gas industries - Steel pipe for pipeline transportation systems	The standard specifies requirements for the manufacture of two product specification levels (PSL 1 and PSL 2) of seamless and welded steel pipes for use in pipeline transportation systems in the petroleum and natural gas industries.	Guides the design and manufacturing process of pipelines used in the offloading process. This includes aspects like material specifications, manufacturing processes, inspection, and testing, outlines safety considerations related to pipeline systems, includes requirements for handling a range of pressures and temperatures and includes provisions for quality management during the manufacturing process that ensure CO_2 offloading system meet necessary quality requirements.
ISO 3183-3:1999	Petroleum and natural gas industries - Steel pipe for pipelines - Technical delivery conditions	The standard specifies the technical delivery conditions for unalloyed and alloyed (except stainless) seamless and welded steel pipes.	Indirectly relevant in situations where pipelines are used for the transfer of captured CO_2. Could be used to guide the manufacture of these pipelines, ensuring they are safe and reliable for this purpose, provides specifications about pressure conditions in the pipelines, defines requirements for material used in the manufacture of pipes.

Standards	Title	Description	Applicability
ISO 10380 : 2012	Pipework - Corrugated metal hoses and hose assemblies	The standard specifies the minimum requirements for the design, manufacture, testing and installation of corrugated metal hose and metal hose assemblies.	Applicable to the design and manufacture of the hose assemblies that will be used in the transfer of LCO_2 from ship-to-ship, ship-to-shore, and ship-to-floating storage. The standard provides guidelines for the design, manufacture and testing of metal hoses.
ISO 21012 : 2018	Cryogenic vessels - Hoses	The standard specifies design, construction, type, and production testing, and marking requirements for non-insulated cryogenic flexible hoses used for the transfer of cryogenic fluids within the following range of operating conditions: working temperature: from −270 °C to +65 °C; nominal diameter (DN): from 10 to 100.	Relevant in the selection of materials for different parts of the system that will come into contact with the LCO_2, it ensures the safety of the operation, as it can help prevent the selection of materials that might become brittle or otherwise fail under cryogenic or sub-zero conditions, helps engineers understand how different materials might react with LCO_2 under varying pressures and temperatures, demonstrates regulatory compliance, informs maintenance procedures, as the compatibility of materials with LCO_2 could affect the longevity and maintenance requirements.
BS EN 13765 : 2018	Thermoplastic multi-layer (non-vulcanised) hoses and hose assemblies for the transfer of hydrocarbons, solvents, and chemicals – Specification	The standard specifies requirements for four types of thermoplastic multi-layer (non-vulcanised) transfer hoses and hose assemblies for carrying hydrocarbons, solvents and chemicals. It is applicable for bore sizes from 25-300 mm, working pressures from four bar to 14 bar and working temperatures from −30 °C to +150 °C.	Applicable to the design and type testing of hose assemblies used in the transfer of LCO_2 captured on vessels manufactured to withstand the characteristics and conditions of LCO_2, including its temperature and pressure.

Standards	Title	Description	Applicability
BS EN 13766 : 2020	Thermoplastic multi-layer (non-vulcanised) hoses and hose assemblies for the transfer of LPG and LNG – Specification	The standard specifies requirements for two types of thermoplastic multi-layer (non-vulcanised) transfer hoses and hose assemblies for carrying LPG and LNG. It is applicable for bore sizes from 25-250 mm, working pressures from 10.5 bar to 25 bar and working temperatures from −196 °C to +45 °C.	Applicable to the design and type testing of hose assemblies used in the transfer of LCO_2 captured on vessels manufactured to withstand the characteristics and conditions of LCO_2, including its temperature and pressure.
ISO 2928 : 2021	Rubber hoses and hose assemblies for LPG in the liquid or gaseous phase and natural gas up to 2,5 MPa (25 bar) — Specification	The standard specifies requirements for rubber hoses and rubber hose assemblies used for the transfer of LPG in liquid or gaseous phase and natural gas, and designed for use at working pressures ranging from vacuum to 25 bar with a temperature range of −30 °C to +70 °C or, for low-temperature hoses (designated LT), within the temperature range −50 °C to +70 °C.	Applicable as a guideline through adaptation for developing safe and efficient hose assemblies and connection systems for the transfer of LCO_2.
ISO 8031 : 2020	Rubber and plastics hoses and hose assemblies — Determination of electrical resistance and conductivity	The standard specifies electrical test methods for rubber and plastics hoses, tubing, and hose assemblies to determine the resistance of conductive, antistatic and non-conductive hoses and the electrical continuity or discontinuity between metal end fittings.	Applicable to providing guidance on the materials to be used in hose and hose assemblies, particularly with regards to their electrical conductivity. This could be relevant when designing and selecting the appropriate materials for the hoses and assemblies used in the LCO_2 transfer process and establishing safety measures during the LCO_2 offloading process.
BS EN 1762 : 2018	Rubber hoses and hose assemblies for LPG (liquid or gaseous phase), and natural gas up to 25 bar (2,5 MPa). Specification	The standard specifies requirements for rubber hoses and hose assemblies used for the transfer of LPG in liquid or gaseous phase and natural gas, and designed for use at working pressures ranging from vacuum to 25 bar with a temperature range of −30 °C to +70 °C or,	Applicable to the design and type testing of hose assemblies used in the transfer of LCO_2 captured on vessels manufactured to withstand the characteristics and conditions of LCO_2, including its temperature and pressure.

Standards	Title	Description	Applicability
		for low-temperature hoses (designated LT), within the temperature range −50 °C to +70 °C.	
EN 1474-2 : 2020	Installation and equipment for LNG - Design and testing of marine transfer systems - Part 2: Design and testing of transfer hoses	The standard specifies guidelines for the design, material selection, qualification, certification, and testing details for LNG marine applications.	The guidelines intended for the design and testing of LNG transfer systems can be extended to LCO_2 in specification of operational procedures, including instructions for connecting and disconnecting transfer systems, safety procedures, ESD procedures that will aid in development of operational protocols for LCO_2 offloading.
IGC Doc 119/04/E	Period inspection of static cryogenic vessels	Covers the periodic inspection and testing of static vacuum insulated cryogenic pressure vessels used in the storage of refrigerated liquefied gases, excluding toxic gases. Considering the design and materials of construction of these vessels, this also includes CO_2 and nitrous oxide.	Recommendations related to the design and operation of storage tanks and transfer equipment, including valves, hoses, and fittings, to ensure that the CO_2 is handled and transferred safely. Also covers recommended safety measures, such as the use of pressure relief valves, ESD systems and fire protection systems, to minimise the risks associated with the handling and storage of LCO_2.
BS 4089:1999	Specification for metallic hose assemblies for LPG and LNG	This standard BS 4089:1999 Specification for metallic hose assemblies for LPG and LNG is classified in these ICS categories: 75.180.01 Equipment for petroleum and natural gas industries in general 23.040.70 Hoses and hose assemblies This BS specify requirements and test methods for metallic hose assemblies used for the loading and	Principles and guidelines can be applied from LPG industries, specifically provides specifications for materials, construction, and performance of the hoses used in the transfer of gases particularly in vapour return lines and outlines procedures for testing and inspecting hoses and hose assemblies to ensure they are safe and fit for purpose.

Standards	Title	Description	Applicability
		unloading of LPG liquefied petroleum gases under pressure. The metallic hose assemblies are suitable for use at a pressure of 25 bar and temperatures from −200 °C to 70 °C.	
API 521	Pressure relieving and depressurising systems	Applicable to pressure-relieving and vapour de-pressurisng systems that provides aid in the selection of the system that is most appropriate for the risks and circumstances involved in various installations.	Applicable to the design and operation of the systems to capture and offload CO_2 from ships, as these systems will likely involve pressurised storage and transport of the CO_2. The standard can inform the design of the pressure relief systems and other safety features related to the handling of pressurised CO_2.

4.2.2.3 Onshore – Storage Standards

Standards	Title	Description	Applicability
ISO TR 27923: 2022	Carbon dioxide capture, transportation and geological storage — Injection operations, infrastructure and monitoring	The technical report provides description of existing legal frameworks, information of CO_2 injection facilities including aspects of materials used and well design considerations, current practices in operational projects including monitoring, safety and reporting requirements associated with both surface and downhole components of CCS projects.	The technical report focuses on the geological storage of captured CO_2 and the applicability to the study may be limited to understanding the requirements of geological storage of captured CO_2, and monitoring, safety and reporting aspects that may be relevant to OCCS.
ISO TR 27921: 2020	Carbon dioxide capture, transportation, and geological storage — Cross cutting Issues — CO_2 stream composition	The technical report aims to describe the main compositional characteristics of the CO_2 stream downstream of the capture unit and identify the impacts of impurities on all the components of the CCS	The document provides vital information on effects of the quality of the captured CO_2 on the operation of the whole CCS chain. The impurities in the CO_2 stream can influence the injectivity, storage capacity and the reactivity in

Standards	Title	Description	Applicability
		chain including the transportation, injection and storage.	geological reservoirs, and thus places quality requirements on the captured and offloaded CO_2 from the ships.
CGA G-6.1	Standard for Large Insulated Liquid Carbon Dioxide Systems at User Sites	The standard covers the design, location, installation, operation, and maintenance of liquid CO_2 supply systems located at user sites where each container has a liquid capacity of greater than 1000 lb, which the industry often refers to as bulk systems	The guidance is applicable to the design and construction of insulated LCO_2 bulk storage tank or container for storage of captured LCO_2, transportation of offloaded LCO_2 and storage of LCO_2 at shore installations.
ISO 20421-1 : 2019	Cryogenic vessels — Large transportable vacuum-insulated vessels — Part 1: Design, fabrication, inspection and testing	The standard specifies requirements for the design, fabrication, inspection and testing of large transportable vacuum-insulated cryogenic vessels of more than 450 litre volume, which are permanently (fixed tanks) or not permanently (demountable tanks and portable tanks) attached to a means of transport, for one or more modes of transport.	The standard is applicable with LCO_2 being one of the fluids explicitly covered in the document and provides requirements for the design, fabrication, inspection and testing of large transportable vacuum-insulated cryogenic vessels, even if the temperatures are not essentially at cryogenic levels.
ISO 21028-2 : 2018	Cryogenic vessels – Toughness requirements for materials at cryogenic temperature – Part 2: Temperatures between -80 °C and -20 °C	The standard specifies the toughness requirements of metallic materials for use at temperatures between −20 °C and −80 °C to ensure their suitability for cryogenic vessels. This document is applicable to fine-grain and low-alloyed steels with specified yield strength ≤460 N/mm^2, aluminium and aluminium alloys, copper and copper alloys and austenitic stainless steels.	This standard is relevant to the handling and storage of substances like LCO_2 which must be stored at low temperatures, even though not essentially at cryogenic temperatures. The standard can be used in the selection of metallic materials for LCO_2 storage vessels onboard ships with a toughness commensurate with the design temperatures envisaged for LCO_2 and without risk of failure due to the low temperatures and

Standards	Title	Description	Applicability
			considerations for the equipment in the transfer process.
BCGA Code of Practice CP26	Bulk Liquid Carbon Dioxide Storage at Users' Premises	The code of practice provides guidance for installation, operation, and maintenance of static insulated bulk liquid CO_2 storage systems at users' premises of individual capacity of up to 250,000 litres.	The guidance is applicable to static insulated bulk storage of LCO_2 onshore storage tanks.

4.2.2.4 Onshore – Safety Standards

Standards	Title	Description	Applicability
ISO TR 27918 : 2018	Lifecycle risk management for integrated CCS projects	The technical report intends to address the broad lifecycle risk management issues for integrated CCS projects, specifically with risks that affect the overarching CCS project or risks that cut across capture, transportation, and storage affecting multiple stages.	The technical report is an useful information source in the integration of the individual stages of OCCS, and for addressing the overarching and cross - cutting risks that apply to all the elements of the CCS chain.
ISO 17349 : 2016	Petroleum and natural gas industries — Offshore platforms handling streams with high content of CO_2 at high pressures	The standard contains provisions for the design of offshore plants handling CO_2 rich streams separated from the produced natural gas at high pressures (>10% CO_2 molar concentration) that are typically injected to enhance oil recovery from the reservoirs and avoid its release to the atmosphere.	The applicability of the standard is to the extent of the safety aspects detailed on the impacts of the loss of containment of CO_2 and related hazards identification and risk assessment.

Standards	Title	Description	Applicability
ISO 21013-1	Cryogenic vessels - Pressure relief accessories for cryogenic service Part 1: Reclosable pressure-relief devices	The standard specifies the requirements for the design, manufacture, and testing of pressure relief valves not exceeding a size of DN 150 for cryogenic service, i.e., for operation with cryogenic fluids below −10 °C in addition to operation at ambient temperatures from ambient to cryogenic.	Applicable to the design of LCO_2 storage and transfer systems with LCO_2 temperatures within these systems expected to be within the scope of this standard, although not expected to reach cryogenic levels.
ISO 21013-2	Cryogenic vessels - Pressure-relief accessories for cryogenic service Part 2: Non-reclosable pressure-relief devices	The standard specifies the requirements for the design, manufacture, and testing of pressure relief valves for cryogenic service, i.e., for operation with cryogenic fluids below −10 °C in addition to operation at ambient temperatures from ambient to cryogenic. Note: This document is applicable to valves not exceeding a size of DN 150 designed to relieve single-phase vapours or gases.	Applicable to the design of LCO_2 storage and transfer systems with LCO_2 temperatures within these systems expected to be within the scope of this standard, although not expected to reach cryogenic levels.
ISO 31010 : 2019	Risk management - Risk assessment techniques	The standard provides guidance on the selection and application of risk assessment techniques to assist in making decisions where there is uncertainty, to provide information about particular risks and as part of a process for managing risk.	Applicable to identify and assess the risks associated with the offloading of onboard captured CO_2 during port calls. The risk assessment process can help identify the potential hazards and risks associated with the offloading process, such as the risk of leakage or spills during transfer, the risk of equipment failure or malfunction, and the risk of human error or accidents.
ISO/TS 18683 : 2021	Guidelines for safety and risk assessment of LNG fuel bunkering operations	The document provides guidance on the risk-based approach to follow for the design and operation of the LNG bunker transfer system, including the interface	Applicable to the development of a bunkering site and facility and the LNG bunker transfer system

Standards	Title	Description	Applicability
		between the LNG bunkering supply facilities and receiving LNG fuelled vessels.	and elements of which can be adapted for LCO_2 offloading.
CGA G-6.7	Safe handling of liquid carbon dioxide containers that have lost pressure	The guidance provides information to personnel to ensure that CO_2 containers that have lost pressure and could contain solid CO_2 (dry ice) or liquid CO_2 at temperatures less than the minimum design metal temperature (MDMT) are safely repressurized before being returned to service.	The scenarios considered in this study focus on LCO_2 handling and storage at low and medium pressure. In scenarios where these storage tanks lose pressure, this standard provides guidelines for personnel on safely repressurising CO_2 containers that may contain dry ice or liquid CO_2 at temperatures below the MDMT. This ensures containers are safe for reuse after losing pressure which will form part of the development of procedures.
OSHA CFR 1910.132	PPE - General Requirements	Set of standards focused on helping improve workplace safety using PPE. The PPE covered under this set of standards includes items that are designed to protect the eyes, face, head, and extremities. This includes, but is not limited to, respiratory devices, protective shields, protective eyewear and protective clothing.	The applicability of this standard would follow in development of a hazard assessment of the offloading process, from which, it will identify the appropriate PPE for workers involved in the offloading process. This could include protective clothing, gloves, eye and face protection, and respiratory protection, depending on the specific hazards identified.
NFPA 59A	Standard for the Production, Storage and Handling of LNG	This standard provides minimum fire protection, safety, and related requirements for the location, design, construction, security, operation, and maintenance of LNG plants.	The standard does not specifically detail PPE requirements, however it emphasises the importance of safety and need for appropriate protective measures when handling cryogenic liquids which can be transferrable to handling of LCO_2. These include cryogenic safety, handling LCO_2, can pose risks such as cold burns and frostbite, therefore, PPE that protects against

Standards	Title	Description	Applicability
			extreme cold, such as insulated gloves and face shields, may be necessary. PPE should be suitable for chemical safety too as LCO_2 can also pose chemical hazards. If the LCO_2 were to vaporise, it could displace oxygen and create a risk of asphyxiation, therefore, respiratory protection may be necessary in certain situations.
EN 511:2006	Protective gloves against cold	Specifies the requirements and performance levels of work gloves against cold as low as -50°C. Protective devices against convective cold, contact cold and water penetration.	The applicability of this standard follows requirements to adhere gloves to convective and contact protection cold down to -50°C. In the context of this study, LCO_2 is extremely cold, and contact can cause cold burns and frostbite. Gloves that meet the EN 511:2006 standard would provide protection against these hazards during the handling and transfer of LCO_2. It is also specific for tasks being performed. The standard includes three performance levels for resistance to convective cold (performance level 0-4), contact cold (performance level 0-4), and water permeability (performance level 0 or 1). The appropriate performance levels would depend on the specific conditions and tasks.
OSHA 29 CFR 1910.134	Respiratory protection	Standard set by the OSHA in the United States. This standard specifically pertains to respiratory protection. It provides requirements for program administration, worksite-specific procedures, respirator selection, employee training, fit testing, medical evaluation, and respirator use, cleaning, maintenance and repair.	The applicability of this standard would follow in development of a hazard assessment of the offloading process, from which, it would identify appropriate respiratory protection for workers involved in the offloading process. This could range from simple air-purifying respirators to

Standards	Title	Description	Applicability
			more complex supplied-air respirators or self-contained breathing apparatuses. A respiratory protection program should also formalise the selection of respiratory protection in accordance with the requirements of standard, which include procedures for selecting respirators, medical evaluations of employees, fit testing, routine and emergency use procedures.
OSHA 29 CFR 1910.1200	Hazard Communication	Standard set by the OSHA in the United States, also known as the Hazard Communication Standard (HCS). This standard is designed to ensure that the hazards of all chemicals produced or imported are classified, and that information concerning the classified hazards is transmitted to employers and employees. The transmittal of information is to be accomplished by means of comprehensive hazard communication programs, which are to include container labelling and other forms of warning, safety data sheets and employee training.	The applicability of this standard pertains to the classification of LCO_2 to personnel working with the substance. In respect to safety, following this standard, if LCO_2, is deemed to be classified as a hazardous chemical, hazards associated with it would need to be identified, which could include cold burns, frostbite, and asphyxiation. A safety data sheet (SDS) for LCO_2 would need to be obtained which provides information on the hazards of LCO_2 and recommended PPE.
OSHA 29 CFR 1910.138	Hand Protection	Standard set by the OSHA in the United States. This standard specifically pertains to hand protection. The standard states that employers shall select and require employees to use appropriate hand protection when employees' hands are exposed to hazards such as those from skin absorption of harmful substances; severe cuts or lacerations; severe abrasions; punctures; chemical burns; thermal burns; and harmful temperature extremes.	The applicability of this standard would follow in development of a hazard assessment of the offloading process, from which, it would identify appropriate hand protection for workers involved in the offloading process. This could include gloves that are resistance to cold temperatures, as well as training to ensure that workers are properly trained on the use of hand protection.

Standards	Title	Description	Applicability
NFPA 55	Compressed Gases and Cryogenic Fluids Code	Facilitates protection from physiological, over-pressurisation, explosive, and flammability hazards associated with compressed gases and cryogenic fluids.	The applicability of this standard does not specifically address PPE requirements. However the importance of safety and need for appropriate protective measures when handling LCO_2 are detailed. This includes cryogenic safety from cold liquid CO_2, PPE that protects against extreme cold, such as insulated gloves and face shields, may be necessary as well as pressure safety, transfer of LCO_2 involves pressurised systems, which can pose a risk of injury from sudden release of pressure, protective clothing and eye protection may be necessary.
ANSI Z87.1	Safety Glasses	This standard provides the minimum general requirements, testing methods, and selection, use, and maintenance guidelines for eye and face protection to prevent or mitigate injuries from physical, chemical, or radiation agents.	The applicability in LCO_2 offloading would be in several says, such as impact protection, offloading and transfer of LCO_2 could potentially involve risks of flying particles or other impact hazards, safety glasses or goggles that meet the ANSI Z87.1 standard for impact protection would be necessary. As well as splash protection, there is a risk of LCO_2 splashes during the offloading process, goggles or face shields that meet the ANSI Z87.1 standard for splash protection may be necessary.

4.2.3 Gap Analysis

The gap analysis of the existing standards, guidelines and recommended practices mentioned in the previous section is carried out on the basis of:

- The direct applicability to the process of LCO_2 offloading arrangement from ships.
- The indirect applicability through adaptability of standards to the process of LCO_2 offloading arrangement from ships.

The main constituents of the LCO_2 offloading arrangement are classified into four core categories for a better identification and understanding of the gaps.

- Machinery
- Piping
- Storage
- Safety

This analysis follows a RAG (Red-Amber-Green) system to assess the gaps in accordance with the criteria set out in the table below and shows the extent of the gap in each category in the form of a RAG pie symbol.

Red	Amber	Green
Standards are not available for LCO_2 storage and offloading for OCCS applications	Standards are not readily available for LCO_2 storage and offloading applications for OCCS but are either applicable to LCO_2 or can be adapted from other industries handling materials with similar characteristics	Standards are readily available for LCO_2 storage and offloading for OCCS applications

4.2.3.1 Maritime Standards

Category	Coding	Gap review	Implication to LCO_2 offloading from ships
Machinery		There are currently no regulatory standards pertaining to the ship machinery envisaged in the arrangements of LCO_2 offloading from ships. However, the assigned gap coding is based on the following standards through direct applicability or indirect adaptability. Classification society rules are published with requirements for OCCS including associated machinery and electrical systems taking a risk-based alternative design and goal-based rules approach, and the key aspects are: - Design requirements of reliquefaction and refrigeration systems for pressure and temperature controls - Design and testing requirements of compressors, separators, pressure vessels, heat exchangers and pumps - Design requirements of pressure relief and venting systems taking into account anticipated impurities in the LCO_2 stream The IGC Code provides the machinery requirements for liquefied gases as cargo including the carriage of LCO_2 but does not cover OCCS, and is supplemented by Class rules for Ships for the Carriage of Liquefied Gases in Bulk. The existing LPG/LNG regulatory standards, guidelines as well as recommended practices towards ship machinery associated with storage, handling, and offloading of LPG/LNG as cargo as well as LNG as fuel onboard are available and adaptable to LCO_2.	In the absence of a regulatory framework within the maritime sector, the classification society rules provide for the requirements of machinery associated with OCCS and are expected to form the basis of the regulatory framework covering the machinery onboard ships including arrangements of LCO_2 offloading from ships. The IGC code, although not directly applicable to LCO_2 offloading from ships, provides the requirements of machinery for the system that can be adapted for the development of requirements for LCO_2 transfer and offloading systems. The maritime standards of LPG/LNG are relevant to LCO_2 through adaptability but are not applicable to LCO_2. However, they provide valuable information vital in the development of machinery requirements for LCO_2 offloading from ships.

Piping			There are currently no regulatory standards pertaining to the ship piping system envisaged in the arrangements of LCO_2 offloading from ships. However, the assigned gap coding is based on the following standards through direct applicability or indirect adaptability. Classification society rules are published with requirements for piping arrangements for OCCS and key aspects are: - Materials for the piping systems need to comply with the appropriate class rules and take into account the effect of corrosion from impurities in the gas stream - LCO_2 offloading arrangements are to comply with the Class rules for ships for the Carriage of Liquefied Gases in Bulk, and for ships using gases or other Low-flashpoint Fuels	In the absence of a regulatory framework within the maritime sector, the classification society rules provide for the requirement of piping systems associated with OCCS and are expected to form the basis of the regulatory framework covering the piping systems onboard ships including arrangements of LCO_2 offloading from ships.
			The IGC Code provides requirements for piping systems of liquefied gases as cargo including the carriage of LCO_2 but does not cover OCCS, and is supplemented by Class rules for ships for the Carriage of Liquefied Gases in Bulk.	The IGC code, although not directly applicable to LCO_2 offloading from ships, provides the requirements for piping systems that can be adapted for the development of requirements for LCO_2 transfer and offloading piping systems.
			The IGF Code provides requirements for piping systems of bunkering and transfer arrangements on ships using low-flashpoint fuels including LNG and is supplemented by Class rules for ships using gases or other Low-flashpoint Fuels.	The IGF Code although not directly applicable to LCO_2 offloading from ships, provides insight in development of requirements given that low-flashpoint fuels including LNG that shares similarities with LCO_2
			The existing LPG/LNG regulatory standards, guidelines as well as recommended practices towards ship piping systems associated with storage, handling, and offloading of LPG/LNG as cargo as well as LNG as fuel onboard are available and adaptable to LCO_2.	The maritime regulatory standards of LPG/LNG are relevant through adaptability but are not applicable to LCO_2. However, they provide valuable information vital in the development of piping systems requirements for LCO_2 offloading from ships.

Storage			There are currently no regulatory standards pertaining to the storage arrangements envisaged in the arrangements of LCO_2 offloading from ships. However, the assigned gap coding is based on the following standards through direct applicability or indirect adaptability. Classification society rules are published with requirements for storage arrangements of OCCS and key aspects are: - Storage tanks used for the LCO_2 containment are to be independent Type-C tanks - Materials for the storage tank need to comply with the appropriate class rules and take into account the effect of corrosion from impurities in the gas stream The IGC Code provides the storage system requirements for liquefied gases as cargo including the carriage of LCO_2 but does not cover OCCS, and is supplemented by Class rules for Ships for the Carriage of Liquefied Gases in Bulk. The existing LPG/LNG regulatory standards, guidelines as well as recommended practices towards storage systems associated with storage, handling, and offloading of LPG/LNG as cargo as well as LNG as fuel onboard are available.	In the absence of a regulatory framework within the maritime sector, the classification society rules provide for the requirement of storage of captured CO_2 and are expected to form the basis of the regulatory framework covering LCO_2 storage requirements onboard ships. However, a regulatory standard on purity of LCO_2 specifying limits of impurities is needed. Also, some compatibility of storage systems in terms of storage conditions is needed. Requirements need to be defined for the characterisation of the LCO_2 captured onboard a ship (noting different geological storage sites have specific conditions (i.e., pressure, temperature and impurities) which the offloaded CO_2 must match in order to enable CO_2 to be stored. Port reception facilities and ship operators will require knowledge of such conditions at the point of offloading). The IGC code although not directly applicable to LCO_2 offloading from ships, provides the requirements for storage systems that can be adapted for the development of requirements for LCO_2 transfer and offloading systems.

Category	Coding	Gap review		Implication to LCO_2 offloading from ships
				The maritime regulatory standards of LPG/LNG are relevant through adaptability but are not applicable to LCO_2. However, they provide valuable information vital in the development of storage systems requirements associated with LCO_2 offloading from ships.

Safety			There are currently no regulatory standards pertaining to the safety aspects in the LCO_2 offloading from ships. However, the assigned gap coding is based on the following standards through direct applicability or indirect adaptability. Classification society rules are published with operational safety requirements for OCCS and key aspects are: - Emergency shutdown systems - Ventilation systems - Monitoring, control and alarm systems - Fire protection and personal protection However, the standards for purity for offloading captured LCO_2 are not set out. The IGC Code provides for operational safety requirements for liquefied gases as cargo including the carriage of LCO_2 but does not cover OCCS, and is supplemented by Class rules for Ships for the Carriage of Liquefied Gases in Bulk. The IGF Code provides requirements for assessment of risks involved in the transfer and handling of low-flashpoint fuels including LNG, but is not applicable to LCO_2. The existing LPG/LNG regulatory standards, industry guidelines as well as recommended practices towards operational safety associated with storage, handling, and offloading of LPG/LNG as cargo as well as LNG as fuel onboard are available. The STCW Convention provides for minimum training and qualification requirements for the Master, officers and crew on liquefied gas tankers and ships subject to the IGF Code. The MARPOL Convention does not account for onboard captured CO_2 as waste stream. There is no standard available for measurement and accounting of LCO_2 offloaded from vessel. Requirements for port reception facilities for the offloading of CO_2 are needed.	In the absence of a regulatory framework within the maritime sector, the classification society rules provide safety requirements for OCCS and are expected to form the basis of the regulatory framework covering the safety aspects onboard ships including arrangements of LCO_2 offloading from ships. The IGC code, although not directly applicable to LCO_2 offloading from ships, provides the requirements for operational safety that can be adapted for the development of requirements for LCO_2 transfer and offloading systems. The IGF Code although not directly applicable to LCO_2 offloading from ships, provides insight in development of operational safety requirements given that low-flashpoint fuels including LNG that shares similarities with LCO_2 The maritime regulatory standards of LPG/LNG are relevant through adaptability but are not applicable to LCO_2. However, they provide valuable information vital in the development of operational safety requirements associated with LCO_2 offloading from ships.

Category	Coding		Gap review	Implication to LCO_2 offloading from ships
				The STCW Convention and Code although not directly applicable to LCO_2 offloading from ships, provides the insight if additional training and qualification is required, and inform these requirements for development of policy development.

4.2.3.2 Onshore Standards

Category	Coding		Gap review	Implication to LCO_2 offloading from ships
Machinery	⊕	⊕ ⊕	There exist regulatory standards, guidelines as well as recommended practices towards machinery requirements for onshore CCUS plants handling LCO_2. Similarly, there exist standards, guidelines as well as recommended practices towards machinery requirements for onshore LPG/LNG plants.	The onshore standards of machinery for LCO_2 handling in CCUS plants although relevant, are not applicable to LCO_2 offloading from ships. However, elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships. Similarly, the onshore machinery standards of LPG/LNG are not applicable to LCO_2 offloading from ships, but elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships.

Category	Coding		Gap review	Implication to LCO_2 offloading from ships
Piping			There exist standards, guidelines as well as recommended practices towards piping systems requirements for onshore CCUS plants handling LCO_2. Similarly, there exist regulatory standards, guidelines as well as recommended practices towards piping system requirements for onshore LPG/LNG plants.	The onshore standards of piping systems for LCO_2 in CCUS plants although relevant, are not applicable to LCO_2 offloading from ships. However, elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships. Similarly, the onshore piping standards of LPG/LNG are not applicable to LCO_2 offloading from ships, but elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships.
Storage			There exist regulatory standards, guidelines as well as recommended practices towards storage requirements for onshore CCUS plants. However, there is a lack of standards pertaining to specific use of LCO_2 storage tanks for maritime applications i.e., corrosion factors during transport. Similarly, there exist standards, guidelines as well as recommended practices towards storage system requirements for onshore LPG/LNG plants. The gap of corrosion factors in LCO_2 storage tanks can be filled with standards and experience highlighted in LPG/LNG applications taking into consideration the corrosion effect of the impurities in the captured CO_2.	The onshore standards of LCO_2 storage for CCUS plants although relevant, are not applicable to LCO_2 offloading from ships. However, elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships. Similarly, the onshore storage standards of LPG/LNG are not applicable to LCO_2 offloading from ships, but elements of these standards can be adapted in the development of standards for LCO_2 offloading from ships.

Category	Coding	Gap review		Implication to LCO$_2$ offloading from ships
Safety			There exist standards, guidelines as well as recommended practices towards operational safety for onshore CCUS plants handling LCO$_2$. Similarly, there exist standards, guidelines as well as recommended practices towards operational safety requirements for onshore LPG/LNG plants.	The onshore standards for operational safety in handling of LCO$_2$ in CCUS plants although relevant, are not applicable to LCO$_2$ offloading from ships. However, elements of these standards can be adapted in the development of standards for LCO$_2$ offloading from ships. Similarly, the onshore operational safety standards of LPG/LNG are not applicable to LCO$_2$ offloading from ships, but elements of these standards can be adapted in the development of standards for LCO$_2$ offloading from ships.

5. Design Principles and Guidelines for Offloading Liquid CO_2

The intent of this chapter is to develop and propose detailed principles and guidelines that govern offloading of onboard captured liquefied CO_2 to onshore and offshore storage facilities. Formal guidance specifically on the design and use of offloading systems for onboard captured liquid CO_2 is not yet available. This chapter forms a consolidated foundation to capture philosophy and therefore enable progress of the feasibility and development of onboard carbon capture. This chapter covers the following scope:

- Develops detailed principles/guidelines that govern onboard captured CO_2 offloading and designs for storage terminal under different transfer modes (varying pressure and temperature): ship-to-ship, ship-to-shore;
- Specify the technical requirements of interfaces of the capturing and receiving vessels, as well as the requirement for ship-to-shore offloading; and in association with the proposed integrated system (liquid CO_2 offloading) and associated safety equipment;
- The analytical methods and verification procedures to measure the quantity and quality of liquid CO_2 during custody transfer.

This chapter includes principles, guidelines and procedures based on first principles, engineering experience and relevant material from similar, more established processes and builds on existing standards governing LCO_2, LNG and LPG handling as specified in chapter 4. The document focuses on those aspects which govern onboard captured CO_2 offloading and associated storage terminals as covered in the selected concept scenarios chosen in this study.

It should be noted that figures and guidelines relating to liquid CO_2 offloading in this document are in the concept stage and should not be taken as standard for live operations.

Four concepts have been short listed in this study to encompass the most likely solutions for near-term and at scale offloading applications whilst also aiming to cover the breadth of applications possible. The shortlisting process of these concepts has been detailed in Chapter 3. These design guidelines focus on the four concepts, whilst being adaptable by the reader to apply to additional concepts.

The concepts are briefly described as:

- Concept 1: Ship-to-shore offload from a tanker at a bulk liquid terminal.
- Concept 2: Ship-to-ship offload at anchorage from a bulk carrier to intermediate LCO_2 receiving vessel then LCO_2 receiving vessel offloads to a floating CO_2 storage vessel.
- Concept 3: Ship-to-ship offload at anchorage from bulk carrier to intermediate LCO_2 receiving vessel then ship-to-shore offload from LCO_2 receiving vessel to a bulk liquid terminal.
- Concept 4: Ship-to-shore offload of LCO_2 ISO tank containers on-board a container ship to cargo terminal.

This chapter aims to provide an understanding of the primary considerations that may be taken into account for the design of an LCO_2 storage and offload system for the above-mentioned shortlisted concepts. The elements discussed here primarily include ambient design temperatures, maximum and minimum design temperatures and pressures of offloading process, metocean conditions, testing requirements, measurement of offloaded LCO_2 and considerations of marine infrastructure. The liquid CO_2 properties described in chapter 1 would need to be taken into consideration and form the basis for further design issues discussed below. Chapter 1.3 provides the properties of liquid CO_2 used to form the basis of chemical foundations for the guidelines proposed. The properties have been selected to represent a composition similar to that expected as an output from onboard carbon capture technology. It should be noted that this is an evolving technology and different properties may be established in the future. The user should note that any composition used outside of this definition, may require different design considerations.

General design principles are discussed in section 5.1 to 5.4. These cover the initial and more general design considerations, normally defined at the early stages of design. Principles and guidelines have been documented in detail in Section 5.5 to 5.14. These sections cover an array of topics, offering insights to guide the design process, promoting operational reliability and effectiveness.

5.1 Design Temperature

The following sections defines the associated design temperatures that need to be considered when specifying LCO_2 systems. These are described as:

- Ambient design temperature: Environmental temperature under which the system is expected to operate. This parameter affects heat transfer from the environment to the system and should be considered in design aspects such as insulation and refrigeration capacities. Maximum and minimum ambient design temperature is critical for components exposed to environmental conditions, such as storage tanks and associated piping.
- Process design temperature: Process design temperature represents maximum and minimum temperatures that equipment and system is designed to safely withstand. It is determined based on anticipated operating conditions, safety factors and potential extreme conditions.
- Process operating temperature: Process operating temperature represent usual range of temperatures at which the system or equipment operates under normal conditions. These are lower than the design temperature to provide a safety margin. Process system should incorporate measures to control and maintain temperature within operating temperature to preserve phase conditions of CO_2. These could include insulation, active cooling or heating systems depending on specific application and operating conditions.

5.1.1 Maximum Ambient Design Temperature

Maximum ambient design temperatures are defined by the IGC Code and Class rules. For normal service, the upper ambient design temperature shall be 32 °C for sea and 45 °C for air.

For service in particularly hot or cold zones, these ambient design temperatures shall be increased or decreased. The overall capacity of the system shall be such that it can control the pressure within the design conditions without venting to atmosphere.

5.1.2 Maximum Design Temperature

Where the maximum operating temperature cannot be calculated accurately, the maximum design temperature should be determined by adding 20% to the operating temperature.

A high temperature shutdown function, in accordance with ISO 10418 [1] or API RP 14C [2], can limit the maximum operating temperature. This is a safety feature designed to automatically cease operation of the system when a predefined maximum temperature, considered unsafe for operations, is reached. This allows prevention of damage to equipment, avoid unnecessary wear and tear and maintain safety of operations such as phase changes in liquid CO_2. A margin should be included to determine the design temperature.

In regions with varying weather conditions, the offloading procedure must be designed to accommodate a range of temperatures. For instance, in tropical weather conditions where temperatures range from 25°C to 40°C, the system must be designed to handle the increased pressure and temperature or minimise impact of external climatic conditions by implementing sufficient thermal insulation to maintain product conditions which will ensure safe and efficient offloading of LCO_2.

Care should be taken not to define higher design temperature than required when it affects the selection of material and pressure class rating.

5.1.3 Minimum Design Temperature

The minimum design temperature, which dictates the low-temperature properties of the material, is determined by the most stringent of the following factors:

- The minimum operating temperature, which is the lowest temperature reached during normal operation, start-up, shutdown, or process disruptions, minus 5°C of minimum operating temperature.
- The minimum ambient temperature, which is based on available weather data. The safety factors for this should be chosen according to the quality of the weather data.
- The minimum temperature during depressurisation, with an additional 5°C margin. The temperature calculations should at least account for heat transfer between the fluid and vessel, and the most conservative starting conditions for depressurization should be used. These conditions include:
    a. Cooling down to the minimum ambient temperature after shut-in at PSV set pressure and corresponding temperature (including the decrease in pressure during cool down).
    b. Conditions during a start-up operation following a depressurisation.
    c. The minimum operating temperature and maximum operating pressure.

Similarly, the minimum design temperature can be limited by delaying the start-up to preheat the system. If this method is used, it must also be approved by the project owner and documented in the operation manual.

5.2 Design Pressure

The following sections defines the associated design pressures that need to be considered when specifying LCO_2 systems.

5.2.1 Maximum Design Pressure

For systems safeguarded by a PSV, class and statutory regulations establish that high pressure alarm is set at 90% of design pressure. The minimum margin is established to prevent accidental PSV activation. The relationship between high trip pressure and maximum operating pressure is depicted in Figure 5.1.

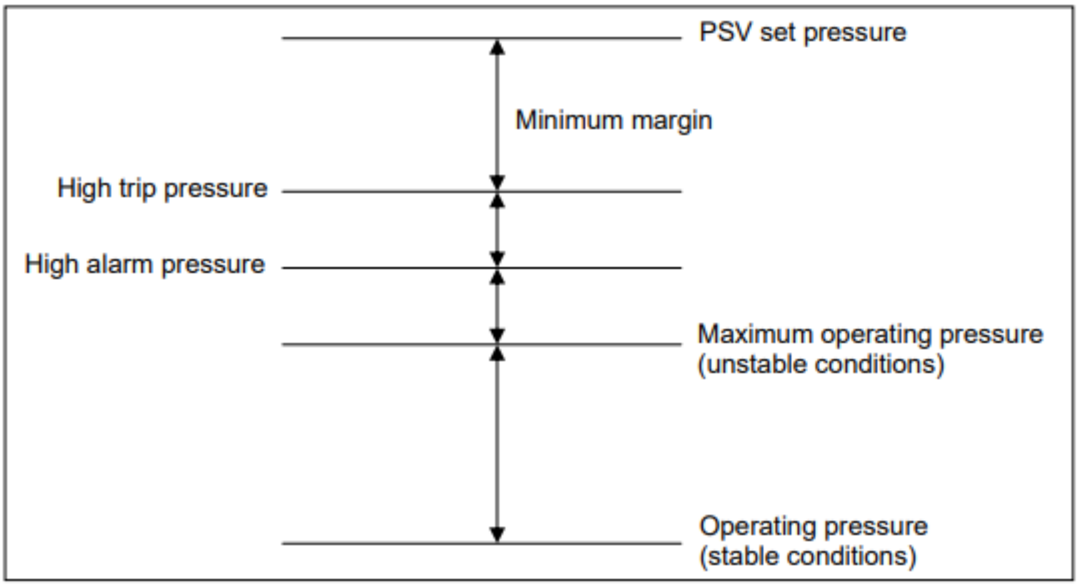


Figure 5.1 – Pressure relations [3]

For more detailed guidance, refer to the relevant pressure relief design codes.

In the absence of precise information, the maximum operating pressure (shut-in pressure) for centrifugal pumps should be calculated as the suction pressure at relieving conditions plus 1.25 times the normal differential pressure generated by the pump.

It is important to avoid specifying a higher design pressure than necessary, as this can influence the choice of material and pressure class rating.

To reduce the need for process relief (full flow), the design pressure should be kept consistent for systems with nearly identical operating pressures.

For piping systems, occasional pressure fluctuations above the design pressure are allowed under certain design codes. This should be carefully considered in accordance with the relevant piping design code. If the project owner allows such variations, the duration and degree of overpressure to which the piping is exposed should be recorded to identify any potential areas of stress or failure in the system before it becomes critical. However, if it is clear that overpressure will not occur more frequently than the piping code allows, logging is not deemed necessary.

5.2.2 Recommended Pressure Drop

In situations where pressure drop is crucial (for instance, when it leads to undesirable phase change), the recommendations in Table 5.1 should be followed. The pressure drop should be proportionally distributed among the given operating pressures. It is important to ensure that during pressure drop situations, pressure is not reduced below triple-point of CO_2, 5.18 bara at temperature of -56.8°C. It is recommended that minimum pressure alarms and safety controls are properly set to prevent solidification of the CO_2.

Table 5.1 – Recommended pressure drop for single phase gas process lines [3]

Operating Pressure (barg)	Pressure Drop (bar/ 100m)
0-35	0.001 to 0.11
35 to 138	0.11 to 0.27
Over 138	P/500 [a]
[a] P is operating pressure in bara.	

5.3 Testing

Safety instrumented secondary pressure protection systems shall be functionally tested to reveal hidden failures to maintain the required safety reliability as defined by International Electrotechnical Commission (IEC) 61508 [4] and IEC 61511 [5]. The required test frequency shall be established, and the following shall apply:

- a system that requires testing more frequent than every third month to achieve the required reliability, is not considered to be sufficiently robust;
- to ensure that system functionality is maintained, the test frequency shall be equal to or more frequent than once a year.

Where leakage or other flow from the upstream system through valves in the safety instrumented system may be crucial to the integrity of the downstream system, the valve leakage rate shall be tested annually.

A high system regularity requirement may dictate the need for parallel systems to enable testing without affecting storage and offloading.

5.4 Isolation

It shall be possible to isolate equipment, instrumentation, valves and process sections during maintenance work to obtain safe working conditions for the maintenance personnel.

The minimum isolation level required shall be thoroughly considered for all systems where intervention during operation can be required. This consideration shall be based on the risk associated with the intervention operation, including:

- requirement for equipment intervention/entry during operation,
- fluid category (level of hazard involved, e.g. flammability, toxicity),
- operating pressure and temperature,
- tank / pipe dimension and system volume,
- duration of operation,
- frequency of operation.

5.5 Measurement (Quality & Quantity)

Understanding the LCO_2 quantity and quality will be necessary as part of the transfer of ownership and to ensure safe processing and mixing with other batches at the storage facility. During offloading and storage of LCO_2, it is important to:

- Monitor process efficiency/phase changes
- Check for density calculation (mass flow measurement)
- Ensure integrity of piping and measurement equipment
- Ensure harmful impurities are not present in CO_2 before storage
- Reduce operational inefficiencies caused by impurities
- Ensure water limits are not exceeded as wet CO_2 causes severe corrosion

These steps would apply for all transfer and storage modes of LCO_2. The following should be considered where determining the quality and quantity is required in the offloading system during piping transportation and LCO_2 storage.

5.5.1 LCO_2 Offload

5.5.1.1 Mass Flow and Density

A fixed meter to measure quantity of offloaded LCO_2 should be installed upstream of storage facilities. Mass flow measurement is recommended for liquid CO_2 applications as traditional technologies such as volumetric measurement would be unsuitable due to the temperatures of LCO_2 (-20 °C to –54 °C) which create mechanical stresses that cause mechanical flow metering equipment to become less accurate.

Some process systems will include a vapour return line therefore mass flow measurement shall also be installed here to account for amount of vapour return from total mass of LCO_2 offloaded.

Coriolis metering technology is recommended as it provides reliable CO_2 measurement data in critical applications throughout transportation and offloading. Coriolis meters are able to measure multiple variables, such as mass flow, density, temperature, phase fraction conditions which allows continuous measurements with entrained liquids in gas or entrained gas in liquids. Measurements are taken by combining data from meters with process variables, such as density of liquid and gas at standard conditions, which allows detection of the presence of entrained water in CO_2 stream which can be actioned to mitigate the risk of corrosion.

Figure 5.2 – Example of Coriolis metering technology [6]

5.5.1.2 Concentration and Composition

A fixed meter to analyse quality or composition of offloaded LCO_2 should be installed at the most appropriate location during the offloading process to confirm compliance with downstream storage facilities specification requirements.

In order to determine the LCO_2 quality or composition of the liquid during offloading, it may be a requirement to take a representative sample of LCO_2 and transform it to a vapor (vaporisation). This task would be performed by equipment named "Sampling and Vaporisation" equipment.

LCO_2 sampling may include three successive operations:

- Taking a representative sample of LCO_2
- Perform a complete and un-fractionated vaporisation
- Conditioning the vapour sample which involves taking sample to conditions suitable for gas chromatography apparatus before transporting it to the Gas Chromatograph

Sampling method can be continuous or intermittent. Regardless of method, LCO_2 sample collected through sample probe installed into the LCO_2 transfer line is gasified in a LCO_2 sample vaporiser. This equipment may consist of the following parts:

- Sample probe
- LCO_2 Sample Vaporiser
- Ancillary Devices (pressure gauges, pressure regulators, thermometers, accumulator, holder, valves, gas sample compressor, etc.)

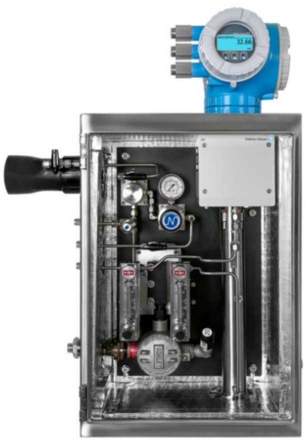


Figure 5.3 – Example of tunable diode laser absorption spectroscopy (TDLAS) gas analysers [6]

Sampling period for LCO_2 transfer shall be carried out continuously at a constant LCO_2 offload flow rate. In case of sudden change in the flow rate or in the pressure in the LCO_2 offload line during sampling period due to, for example, an offload pump being tripped or an emergency shut-off device being activated, sampling shall be temporally suspended until the flow rate of LCO_2 is normalised.

Alternatively, concentration and composition measurement of CO_2 purity and its impurities can be measured using a LCO_2 vaporised sample and gas analysers which offer fast, high-resolution spectroscopy measurements that provide near-live data and trend information for operators.

Figure 5.4 – Continuous gas analyser [7]

5.5.1.3 Temperature Measurement

Temperature is a key property of the CO_2 that must be managed. It is beneficial to use non-intrusive measurement which reduces the risk of process leaks by making it possible to achieve accurate process temperature data measurement without the need for thermowells or process penetrations. Meters use a thermal conductivity algorithm with an understanding of the conductive properties of the temperature measurement assembly and piping, which means this surface temperature sensor solution accurately measures internal temperature. This ensures efficiency, safety and the base states of gases and liquids are maintained during processing, transport, and storage.

Figure 5.5 – Non-intrusive temperature transmitter [7]

Figure 5.6 – Example of temperature transmitter [6]

5.5.1.4 Corrosion and Erosion Monitoring

The presence of moisture in CO_2 will cause the formation of carbonic acid which may attack the pipeline or process equipment, therefore online monitoring of piping and process unit corrosion is important to avoid leakages and spillage. Depending on the location of the installation, corrosion monitoring solutions can be wireless, which means wirelessly transmitting the data to the control system for monitoring purposes. It is to be noted that instrumentation is unlikely to be sufficient alone to monitor corrosion and erosion and a combination of wireless monitoring and visual inspection activities on pipework would be required.

Figure 5.7 – Example wireless ultrasonic (UT) sensors [7]

5.5.2 LCO_2 Storage

5.5.2.1 Mass Flow and Density

Moving large volumes of CO_2 from storage location to vessel while maintaining process safety, process integrity and accuracy for delivery of repeatable custody transfer measurements is time consuming and adds complexity. As highlighted in section 4.5.1.1, Coriolis metering technology is also recommended for storage as it measures multiple variables, such as mass flow, density, temperature and phase fraction conditions.

Accurate density measurement is complex if phase is unstable, potentially resulting in the momentary existence of two phases in the system. Coriolis flow meters are the technology able to accurately measure fluids in any phases due to their advanced phase measurement capability.

Figure 5.8 – Coriolis flow meter [7]

Additionally, fork density meters (FDM) can also be used as a redundancy check and allows direct input of external temperature transmitters, pressure transmitters and flow with an accuracy of ±1 kg/m^3 for density and ±0.1% for concentration.

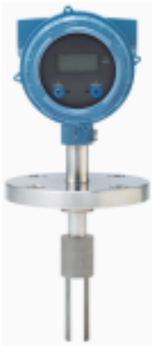


Figure 5.9 – Fork density meter [7]

5.5.2.2 Concentration and Composition

Operation at the CO_2 triple point can only be achieved by maintaining the CO_2 in its liquid state and is critical to avoid interruptions in product transfer and unplanned downtime.

CO_2 conversion to the gaseous phase is required before any composition analysis. This can be done by including an analyser skid system, such as a gas chromatograph, with a heated pre-conditioning sampling system or CO_2-H_2S analysers and water with a heated pre-conditioning sampling system.

Custom-engineered gas chromatographs exist for CO_2 measurement, and these can be used to measure contaminants for online quality assurance.

5.5.2.3 Level Measurement and Overspill Prevention

Pressure and temperature fluctuations can cause phase changes which can lead to leaks, spills and safety events as containment could be compromised. Therefore, ensuring stable conditions and avoiding impurities or humidity is critical.

Differential Pressure (DP) Level measurement with remote seals is highly applicable and reliable. For larger tanks, where the pressure differential becomes more pronounced, a DP level device, with a remote seal to safeguard the transmitter from extreme cold, will ensure consistent and accurate measurement of liquid level. Electronic remote seals would be preferable due to faster response times and reduced maintenance concerns associated with capillary tubes in the harsh environment. Electronic remote sensor systems can be used for measuring level of liquid CO_2 in tanks after low pressure compression.

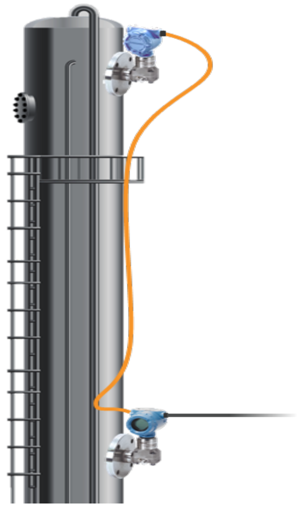


Figure 5.10 – Electronic remote sensors (system [7]

For large tanks, level gauge and tank gauging system solutions are used for tank level control, overfill prevention, and custody transfer.

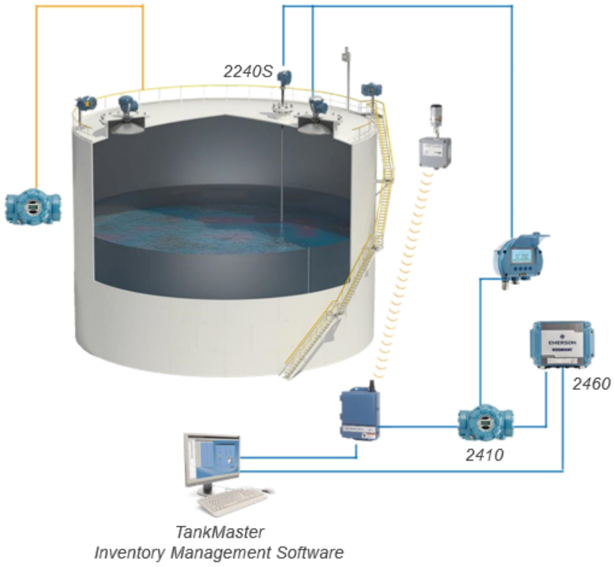


Figure 5.11 – Level gauge and tank gauging system solution [7]

Figure 5.12 – Tank gauging radar and tank gauging servo [6]

Alternatively, continuous level measurement for liquid CO_2 storage could utilise guided wave radar (GWR) technology. GWR offers high accuracy and is not influenced by the fluid's property or external condition whilst coaxial probes ensure a strong signal and consistent performance.

Figure 5.13 –GWR technology [6] [[7]

5.6 Gas Detection

A fixed gas detection system should be installed in areas as per the gas' risk category:

- Risk of fire and/or explosion such as the presence of flammable gases
- Risk of asphyxiation such as leak of one or more asphyxiating gases
- Risk of anoxia/hyperoxia such as insufficient or excessive oxygen supply

Given operations will primarily handle CO_2, only risk of asphyxiation and risk of anoxia are considered.

Each gas detector should be capable of detecting carbon dioxide gas concentrations in air. Alarms will be activated if the CO_2 concentration in air exceeds 5,000 ppm, which is the permissible exposure limit (PEL) set by OSHA [8]. In the context of offloading operations, an automatic shutdown via ESD will be initiated if the concentration reaches 40,000 ppm, which is the Immediately Dangerous to Life or Health (IDLH) level.

5.7 Metocean Conditions

The metocean conditions at the proposed offloading sites need to be evaluated so that the design and operating envelope of the offloading system can be suitably specified. The metocean conditions are then used to determine the environmental loads on the offloading system so that the system can operate safely, without damage in the intended conditions. Both tides, currents, wind (persistent and extreme gusts), waves will influence offloading operations. Metocean conditions should be considered separately at anchorage and at berth; anchorages are typically located offshore in more exposed locations whereas berths are often more sheltered.

On an existing berth, the metocean limits for safe operation of ship-to-shore equipment (loading arms, gantry cranes) should be defined and made available. New equipment for LCO_2 handling would be expected to operate within similar conditions and geometric limits. As liquid CO_2 is a hazardous product, there may be a need to adopt more onerous metocean operating conditions to suit local safety acceptance criteria.

For ship-to-ship transfers at anchorages, there will likely be a need to develop new metocean limitations based around the safe operation of liquid CO_2 transfer hoses between the target vessels in the local environment.

The metocean conditions needing to be investigated would include:

- Tides
- Current – speed and direction
- Wind – speed and direction
- Wave – height and period, including swell
- Temperature – extremes can affect loading and unloading
- Typhoons, hurricanes, tropical storms, squalls, electrical storms.

5.7.1 Tides

This is specifically relevant at ports where arrival and departure at berth is subject to tidal operations, and at terminals completing over-the-tide cargo operations. Vessel operators should not be limited by the tide when offloading LCO_2, as this limits the ability of the vessel to leave berth during a product leak or emergency.

Tides are unlikely to affect vessel operations for offloading LCO_2, although it may be necessary to deploy additional mooring lines.

5.7.2 Currents

River and estuary ports may be subject to strong currents. Coastal ports may also be affected by tidal currents in locations surrounded by islands and archipelagos.

5.7.3 Wind

Extreme or persistent winds can disrupt LCO_2 offloading operations at berth and at anchorage.

Analysis of StS mooring layouts should be completed to determine the wind speed at which the safe working load of the arrangement is exceeded.

At berth, the bulk liquids terminal operator should establish the operational limit of marine loading arms during high winds. This is because wind loading places strain on arms and vessel manifolds.

5.7.4 Typhoons/Hurricanes/Tropical Storms/Squalls

Squalls are relatively unpredictable short bursts in intense wind gusts which result in unsafe mooring conditions. Squall warnings are typically raised for a few hours at a time, although can last up to a few days. It is expected that both ship-to-ship and ship-to-shore transfer of LCO_2 will cease when squall warnings are raised. They are more prevalent in certain areas around the world.

In response to typhoons, hurricanes and tropical storms, it is expected that LCO_2 offloading will cease for all offloading concepts. In the event of an approaching extreme weather event, all vessels will be ordered to clear both anchorages and berths by the harbourmaster. This will interrupt LCO_2 offloading for a few days per weather event as cargo handling ceases, the port is evacuated, and vessels take time to return to port.

5.7.5 Waves

Waves or swells have a significant influence the safe handling of cargo on/off a vessel, namely because the waves may cause the vessel to move in an uncontrolled manner. Wave conditions at berth will be expected to be more controlled or sheltered which will be reflected in the operating ranges for cargo handling equipment.

The window of opportunity for StS transfer of LCO_2 may be limited by wave heights due to excessive relative movement between vessels. The behaviour of relatively small vessels in a ship-to-ship mooring when subjected to swells is not well understood. Noting the influence of this response on the system capacity, this should be better quantified.

The relative size of the two vessels involved in Ship-to-Ship transfer combined with wave heights is key, and directly impacts the uptime for LCO_2 offloading. Hence, a metocean analysis at the proposed location of Ship-to-Ship transfer will be required; uptime offshore will be lower than uptime in sheltered nearshore locations. A persistence analysis will indicate how long the sea state exceeds a certain wave height, which is something that cannot be obtained from wave roses alone.

Limiting wave heights for StS transfer for pairs of vessels can be obtained from the report by OCIMF on Mooring Load Analysis During StS Transfer Operations. The following is a summary of the data trends in the OCIMF report:

- The longer the wave period, the higher the load in the mooring lines, and lower associated limiting significant wave height.
- The influence of the wave period on the size of vessel is more dominant than the relative size differential between the moored vessels.
- Wave height threshold is highest when waves are on the bow, and lowest on beam.
- For the same sized bulk carrier, a smaller LCO_2 receiving vessel has a lower limiting wave height for Ship-to-Ship transfer compared to a larger LCO_2 receiving vessel.
- Daughter-ship (LCO_2 receiving vessel) lines usually exceed their working line load before the mother (bulker/container/tanker) ship's mooring lines. Innermost and shortest lines reach the limit first.
- A laden LCO_2 receiving vessel allows for a higher limiting wave height than a deballasted vessel.

5.7.6 Visibility

As an additional safety measure, good visibility during LCO_2 offloading operations is recommended. Hence, low visibility conditions such as fog are not ideal or safe conditions to transfer LCO_2.

It is expected that offloading at a bulk liquids terminal or container berth can continue 24 hours a day as these existing facilities typically operate at all hours and are well lit.

Offloading StS at anchorage may be restricted to daylight hours. This could be mitigated by VTS and radar systems to position the vessels. There is a greater risk associated with operating in darkness.

5.8 Vessel Condition

The draft and vessel freeboard should be considered when designing all interfaces; it influences the reach of marine loading arms and vessel cranes. The draft of container vessels varies minimally and can be considered constant due to the combination of empty and full containers onboard. However, the draft of bulk carriers and tankers changes significantly when laden compared to when ballast.

Additionally, the laden or ballast vessel state affects stability of StS mooring configurations and the metocean operational limit.

5.9 Marine Infrastructure

5.9.1 On-shore Equipment

5.9.1.1 Vessel Cranes

Hoses for ship-to-ship transfer of LCO_2 are moved into position using lifting equipment, with the aim of avoiding sharp kinks in the hoses. Lifting equipment must also be able to lift pneumatic fenders and sized to accommodate the weight of the hose when full of product. To ensure that lifting equipment is safe to use and able to carry the load within its specification, the safe working load (SWL) of the lifting equipment must be clearly and visibly indicated with the last test date or next test date. Similar to MLAs, the reach of vessel lifting equipment must be adequate so that the hose can be moved between a pair of vessels completing StS transfer. The LCO_2 receiving vessel has a lower freeboard than the offloading ship and so lifting equipment must be able to adequately reach upwards; this difference in freeboard is greatest when the offloading ship is ballasted.

Onboard lifting equipment varies depending on vessel specification. It may include:

- Cargo hose-handling cranes, derricks, davits and gantries
- Cargo loading arm cranes
- Slings, lifting chains and straps

During LCO_2 transfer, the lifting equipment should be adjusted to avoid strain on the hose, manifold and connection. This also ensures the radius of curvature of the hose is within manufacturer's limits. The OCIMF Marine Terminal Operator Competence and Training Guide should be consulted for information on the formal training of personnel engaged in operating lifting equipment. It is to be noted that transfer hoses and lifting equipment are located and maintained by LCO_2 receiving vessel.

5.9.1.2 ISO Tank Container Lifting Equipment

Ship-To-Shore Cranes
ISO tank containers of LCO_2 are offloaded at container terminals via ship-to-shore cranes. Ship-to-Shore cranes lift ISO tank containers directly onto trucks which drive the offloaded LCO_2 to the hazardous cargo port storage area. This is existing infrastructure, already in place at all major container terminals around the world; there is no additional requirement for existing infrastructure. Most major container terminals have an average ship-to-shore handling rate of 30 moves per hour. In large container terminals it is also possible to complete tandem lifts, where two ISO tank containers are offloaded at the same time.

Other Lifting Means

ISO tank containers need to be lifted on and off trucks within the hazardous storage area at the container terminal, and subsequently at location where ISO tank containers are discharged into a single storage tank. Various lifting equipment is used to lift ISO tank containers off trucks. This is not limited to straddle carriers, gantry cranes, reach stackers, heavy container forklifts and telehandlers. Depending on port operations, the ISO tank container may not be lifted off a truck as the prime mover can be detached instead.

5.9.2 Mooring Equipment

5.9.2.1 Mooring Equipment at Berth

It is expected that berths at both container terminals and bulk liquid terminals will provide appropriate mooring equipment for the size of vessel using the berth. The terminal will provide mooring bollards or mooring quick release hooks positioned and sized for the vessels. Mooring lines are typically provided by the vessel; the safe working load of each mooring line should be known to berth-operating personnel.

An LCO_2 receiving vessel will have a small deadweight tonnage compared to the majority of bulk liquid carriers. There may be geometric challenges associated with small LCO_2 receiving vessels directly berthing at a bulk liquid terminal due to its low freeboard. Geometric checks should be completed to ensure that mooring lines are not touching the jetty edge in non-idealised positions. An LCO_2 receiving vessel should offload product at a bulk liquid berth suitable for its size.

5.9.2.2 Mooring Equipment at Anchorage

Mooring equipment for vessels involved in the ship-to-ship transfer of petroleum, chemicals and liquefied gases are detailed in the OCIMF Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases.

- Enclosed fairleads to ensure control of mooring line as the freeboards of the two ships changes.
- Majority of the mooring line would be supplied by the LCO_2 receiving vessel and expected to be synthetic materials. If steel lines are utilised then they should have soft rope tails which can be cut in the event of an emergency.

5.9.3 Fendering

5.9.3.1 Fendering Equipment at Berth

It is expected that berths at both container terminals and bulk liquid terminals will provide appropriate fendering systems for the size of vessel using the berth. Suitable fendering is likely already in place at container and bulk liquid terminals.

Fenders should be capable of withstanding expected loads and should be spaced so that the vessel lies alongside the berth with fenders on the parallel body of the vessel. Fenders should remain on the parallel body of the vessel at all tides and freeboards.

5.9.3.2 Fendering Equipment at Anchorage

The OCIMF StS Transfer Guide recommends pneumatic fenders for use during StS transfer between two vessels at anchorage. Typically, 4 or 5 fenders are required with a diameter of 2 to 2.5m.

5.9.4 Navigation

The berth pocket and navigational approach to a bulk liquids terminal and container terminal should be dredged appropriately to the vessel arriving at berth. An underkeel clearance of 1.0m or 10% vessel draught should be maintained at all times.

The impact of additional vessels to facilitate LCO_2 offloading on vessel traffic should be considered within the anchorages, navigational channel and berths. This is unlikely to be an issue.

5.9.5 Anchorages

Anchorages should be carefully selected to minimise the impact of a LCO_2 leak or spill when undertaking offloading. The following should be considered when identifying suitable StS locations for LCO_2 offloading:

- Select an anchorage adjacent to those with low utilisation.
- Select an anchorage whereby the closest impacted vessels would be other gas carrier vessels. These are likely to have crews more accustomed to dealing and reacting to hazardous gas incidents.
- Select an anchorage based on the prevailing wind conditions, to minimise the impact on vessels in a downwind position. Give preference to the most western, eastern, northern or southern anchorages as appropriate to the prevailing wind. Note that the prevailing wind may change seasonally, and so the offloading location should be adjusted seasonally if relevant. Outer anchorages also provide relatively easier access to the offloading vessel pair if an emergency response is necessary.

5.10 Design Principles for LCO_2 Offloading

5.10.1 Loading Arms

Loading arms are typically rigidly constructed with mechanical articulated joints to allow the required movement during CO_2 transfer to connect to the offloading ship or LCO_2 receiving vessel. They can offer many benefits, including assisted actuation with hydraulic or pneumatic systems as well as easier handling and connection.

Loading arms should be installed at fixed locations at bulk liquid terminal jetties and can offer the possibility to transfer large volumes of LCO_2 at high speed.

The loading arms fixed on land should be capable of the connection and safe transfer of LCO_2 at a range of defined flow rates, within a set of pressure and temperature criteria without any adverse effects or leakage.

The specification of such a ship-to-shore offloading system with loading arm should address the following:

- System compatibility between the jetty/ LCO_2 receiving vessel;
- Compatible with LCO_2 receiving manifold design including removable spool pieces and connections;
- Safety systems compatibility between offloading and LCO_2 receiving vessels;
- Impact of ship motions and environmental conditions (swell, wind speed, sea state, etc.) should be considered;
- Loading arm compatibility with Pre-offloading cool-down processes;

- Compatibility with LCO_2 offloading transfer rate during offloading start-up, full load and topping-off operations;
- Compatibility with the maximum operational pressure and temperature range allowed during the offloading operation.

Importantly, the MLAs also need sufficient operating reach to safely connect to the vessel. The MLA should be designed for:

- The tidal range at berth
- Maximum and minimum freeboard of the vessel at berth. MLAs should be designed to offload LCO_2 from both the largest and smallest vessel expected at berth.
- Maximum and minimum manifold setbacks from the deck edge.
- Horizontal change in vessel position due to drift off and ranging.
- Maximum and minimum spacing when operating alongside other MLAs.

MLAs with a larger reach may be required to service the small LCO_2 receiving vessels at a bulk liquid terminal. The vessel deck may require a higher set of manifolds to remain safely connected when an LCO_2 receiving vessel is laden at the lowest tide.

The specific dimensions of the LCO_2 loading arm will be determined by the specific vessel, port, jetty or berth and the pipe it needs to handle.

5.10.2 Flexible Hoses

Flexible hoses have been successfully used for LCO_2 transfer operations onshore. They should be constructed of composite multi-layer thermoplastics and should be designed to suitable recognised standards, such as such as ISO 21012 [9] , BS 4089 [10], BS EN 13765 [11] or ISO 2928 [11]. It is crucial that they are designed and used correctly, for example, suitably handled and supported throughout the connection, offloading, and disconnection process.

Hoses should be permanently marked with the following information:

- Hose serial number
- Internal diameter of the hose
- Overall weight of complete hose
- Date of manufacture
- Date of proof pressure testing
- Certifying Authority Approval
- The maximum working pressure
- The maximum flow rate
- The maximum and minimum allowable working temperature range

From an operational perspective, the maximum hose size will be governed by the capabilities of the lifting equipment and the offloading manifold construction on-board the LCO_2 receiving vessel.

In determining the length of the hoses to be used, the following should be considered:

- Maximum allowable bend radius of the hose.
- Horizontal distance between the vessels, as governed by the fender diameter.
- Distance between offloading manifold of LCO_2 receiving vessel relative to and the supporting arm/crane reach from the offloading merchant ship.
- Vertical and horizontal vessel movement.
- Any other special design features related to the offloading merchant ship and offloading system to be utilised.
- Relative change in freeboard between the vessels.
- The offloading equipment should be supported by suitable means to prevent excessive load on manifold fittings in accordance with the minimum size of the OCIMF manifold guidelines [12].

The flexible cryogenic hoses for LCO_2 should be typically made of the following principal layers:

- Inner wire: Stainless Steel 316
- Lining: Polyester fabrics and films
- Outer cover: Polyamide
- Outer wire: Stainless steel 316

Depending on the offloading station location and layout, suitable equipment (e.g., saddles, lifting lugs) should be employed to ensure the minimum hose bending radius is not exceeded, and to assist in the support of the hose throughout the transfer operation.

All supporting equipment may be integral to the load restraint system preventing excessive axial and torsional loads on the offloading hose end fittings. Their design load and safety of layout must be considered along with their ability to prevent chafing of the hose(s) and mitigation to avoid damage within the offloading station during an event of ERS activation and hose disconnection. Their design should ensure electrical isolation is maintained between the hose and the ship's structure.

When using cryogenic hoses or a combination of piping/hoses, it is necessary to adhere to the specification and maintenance requirements. These should at least include:

- Design characteristics – hoses should have a leak before failure mode.
- Hose certificate – each hose must be accompanied by a certificate from the Certifying Authority.
- In-Service Testing procedures – these should be developed in accordance with manufacturer's recommendations, or as necessary to verify the integrity of the hose before use. Testing and inspection records must be maintained.
- Storage of hoses – hoses should be stored as per manufacturer's recommendations to minimise the risk of mechanical damage or moisture entrapment.
- Marking - hoses should be marked to ensure usage for correct fluid.
- Couplers specification – correct and standardized couplers should be used to minimise leaks and allow quick release.

The following parameters are the contributing factors in StS offloading flow rates:

- Vessel pump capacity
- Piping capacity (Flexible hose in StS transfer)
- The LCO_2 receiving vessel reliquefaction capacity
- Ambient temperature, which has a direct impact on boil-off rate and hence the above factor.

When there is a large difference in the freeboard between two vessels, the LCO_2 receiving vessel must make allowances for the contents of the hose on completion of transfer.

5.10.3 LCO_2 Pumps

Primary pumps for LCO_2 offload are:

- Submerged Pumps and Deepwell Pumps: Centrifugal pumps with horizontal impellers should be positioned at the deepest part of the LCO_2 storage tank on the ship (i.e., the LCO_2 tank pump well/sump). Their primary function is to facilitate the transfer of LCO_2 to a designated tank storage facility. Additionally, these pumps are crucial for recirculating the LCO_2 to prevent stratification and mitigate risks associated with pressure accumulation in large, stationary LCO_2 storage tanks. The pump design should reflect the unique characteristics of liquid CO_2, such as its high density and low viscosity. The electrical motor powering the pumps maybe located inside the tank (Submerged pump) or outside the tank (Deepwell pump).
- External LCO_2 Pumps: External LCO_2 pumps or booster pumps, usually mounted on skids, are engineered to facilitate the transfer of LCO_2 between pressurised storage tanks on intermediate LCO_2 ship and (i.e., between two type C tanks with high operating pressures) or third party users at substantial flow rates, often exceeding 100 m^3/hr. These pumps are integral to LCO_2 offloading configurations, where the skid hosts the local control panel, inclusive of manifold fittings (T-connectors, Y-connectors) to suit the flange connections of a recipient vessel.

5.10.3.1 Net Positive Suction Head (NPSH)

The transfer of LCO_2 takes place at elevated pressure. The pumping system need to be designed to prevent cavitation in the transfer pumps. When transferring LCO_2 from one pressurised tank to another, the height from the surface of the liquid in the origin tank to the pump suction port is known as the net positive suction head (NPSH). Maintaining the correct NPSH according to the pump performance curve requirements when pumping a pressurised liquid is important to ensure no flash gas bubbles are formed to cause cavitation. In this application, controlling the NPSH could present some challenges. Low NPSH may lead to formation of flash gas bubbles and consequent cavitation, which damages the pump and disrupts offloading of LCO_2.

To avoid this, NPSH may be kept within recommended limits specified by the pump manufacturer. Mitigation measures may include use of variable speed drives on pumps to adjust pump speed and consequently NPSH requirement based on current conditions. In addition, use of pressure control valves or automatic control systems that adjust pump operation based on real-time measurements of NPSH can help to maintain NPSH within acceptable limits. Furthermore, design of the system, including positioning of the pump and design of the suction piping, can be optimised to minimise the impact of changes in the height of the LCO_2 in the tank.

At the suction end of the pump, the LCO_2 condition will be at slightly elevated pressure due to the NPSH requirement if pump is below the tank level, it is therefore suggested that pump should be located at the bottom of the tank. At the discharge end of the pump, LCO_2 exists as a high-pressure liquid. Due to the increase in pressure, LCO_2 will remain as a high-pressure liquid through the pipe until it enters the receiving tank.

5.11 Design Principles for CO_2 Piping Systems

Piping systems for LCO_2 offloading are to be implemented as fixed onshore piping from onshore loading arm to a bulk terminal storage.

Sizing of piping may be in accordance with DNV-RP-F104 [13]. Velocities shall be kept low enough to prevent problems with erosion, water-hammer pressure surges, noise, vibration, and reaction forces. In some cases, a minimum velocity is required.

In vapour lines, gas velocity shall not exceed limits which may create noise or vibrations problems. As a rule of thumb, the velocity should be kept below:

$$V = 175 \times (1/\rho)^{0.43}$$

Where:

ρ - Density of gas (kg/m^3)

V - Maximum velocity of gas to avoid noise (m/s) or 60 m/s, whichever is lowest.

5.11.1 Safety of Pipelines

Offloading LCO_2 presents a number of hazards to the personnel during operations and materials used to construct pipelines. The following sub-sections provide considerations for the safe specification of LCO_2 pipelines.

5.11.1.1 Corrosion

CO_2 is an acidic gas that forms carbonic acid when it reacts with water. This means that the water content of CO_2 transported through carbon steel pipelines needs to be monitored and kept below certain limits to prevent corrosion. These limits are typically dependent on specific pipeline material and operational conditions. As a general rule, water content of less than 50 ppm is often recommended for CO_2 streams to prevent corrosion. The pipeline materials should be chosen accordingly, considering their resistance to corrosion caused by acidic environments. Other impurities in the CO_2 stream can also cause corrosion when they react with water and in some cases may pose a greater risk than carbonic acid. Limits of impurities affecting CO_2 quality foreseen for ship transport are presented in Table 5.2.

It is likely that not a single specification will match every project, and these are most often defined on a project-by-project basis. An acceptable compositional range should be determined and documented based on project-specific studies. Risks associated with each contaminant throughout the carbon capture chain could be included, especially if the specification is not met.

Table 5.2 – Impurities concentration recommended for CO_2 quality in ship transport

Component	Concentration
Water (H_2O)	50 ppm
Hydrogen Sulphide (H_2S)	≤ 9 ppm

Component	Concentration
Carbon Monoxide (CO)	≤ 100 ppm
Sulphur Oxides (SO_x)	≤ 10 ppm
Nitric Oxide/Nitrogen Oxide (NO_x)	≤ 10 ppm
Amine	≤ 10 ppm
Ammonia (NH_3)	≤ 10 ppm
Formaldehyde	≤ 20 ppm
Acetaldehyde	≤ 20 ppm
Mercury	≤ 0.03 ppm
Methane (CH_4)	<0.3% v/v (all non-condensable gases)
Nitrogen (N_2)	<0.3% v/v (all non-condensable gases)
Oxygen (O_2)	≤ 10 ppm
Argon (Ar)	<0.3% v/v (all non-condensable gases)
Hydrogen (H_2)	≤ 50 ppm

5.11.1.2 Ductile and Brittle Fracture Propagation

The thickness and toughness of the pipeline wall should be determined to prevent brittle fracture at normal operating temperatures and during a containment loss event. It is also crucial to prevent or quickly stop ductile fracture. These design considerations should be applied to all parts of the piping system, including welds and fittings.

5.11.1.3 Saturation Pressure

If a dense phase or supercritical CO_2 pipeline ruptures, the concentration of impurities such as N_2, H_2, O_2, and Ar will influence the saturation pressure of the released fluids. This is a significant design factor because the time it takes for the released CO_2 to transition from dense or supercritical phase to gaseous phase will significantly impact subsequent ductile crack propagation.

5.11.1.4 Stream Composition and Flow Assurance

Pipelines designed to transport LCO_2 should consider the range of impurities that may be present in the LCO_2. If LCO_2 from multiple sources is transported, each pipeline section should be designed and operated considering the LCO_2 stream composition within that section. To ensure consistent quality and safety, a common entry specification should be established and complied with, which will regulate the offloading LCO_2 into storage facilities. This specification should define acceptable ranges for impurities to accommodate variations from different sources. Also, due to the potential variability of LCO_2 offloaded, pipeline designers and operators should consider the likely intermittency in flows and the resulting effects of repeated pressure cycling.

5.11.1.5 Modelling Loss of Containment

During a containment loss event, complex interactions will occur between the pipeline, the surrounding environment, and the decompressing fluid. With LCO_2, this is further complicated by the potential for fluid phase changes. This depends on the temperature and pressure, the geometry of the orifice through which the gas is decompressing, and the presence and concentration of impurities. Given the complexity of modelling such a release, designers and operators should use existing outflow models that have been experimentally validated for use with CO_2. Additionally, computational fluid dynamics (CFD) may be used to model releases and help determine separation distances, especially when a LCO_2 pipeline passes through a workplace, an occupied onshore installation, or a populated area.

5.11.1.6 Non-Metallic Components

Impurities in the LCO_2 stream may cause deterioration in non-metallic components such as elastomeric seals used in pipeline valves. Therefore, non-metallic components should only be used in LCO_2 pipelines where they have been certified for CO_2 service and their continued integrity in the presence of likely impurities has been proven.

5.11.1.7 Fluid Hazard Classification

During a containment loss event, significant amounts of LCO_2 are likely to be released from a pipeline. A containment loss event from a dense or supercritical phase LCO_2 presents a lower risk level to a release from a high pressure natural gas pipeline, where LCO_2 release results in ground level concentration build up leading to asphyxiant environments. Therefore, LCO_2 pipeline designers should consider applying an appropriate fluid hazard categorisation, chosen from an established pipeline design code, such as BS PD 8010 [14], to that applied to high pressure natural gas pipelines.

5.11.1.8 Pressure Relief

In addition, Class Rules, IGC codes mandate that all sections of LCO_2 piping that can be isolated (i.e., all LCO_2 piping between two valves) should be fitted with a safety valve. This is to prevent overpressure in the piping and consequent leakage during inadvertent isolation due to the liquid-vapour transition. More importantly, this also protects against any potential fire scenarios on-board ships and storage facilities which will affect LCO_2 piping systems by increase of heat resulting in phase change of LCO_2 leading to over pressurisation. As per industry guidance, it is recommended to have a remote isolation on the PSV inlet to prevent continuous depressurization in case of the relief valve not closing. This is to prevent reaching triple point and consequent solidification of the tank content.

5.12 Design Principles for Intermediate LCO_2 Receiving Vessel

The containment system is a critical aspect of LCO_2 receiving vessel design. The intermediate LCO_2 offloading storage tanks located on the intermediate vessel should be specified as per requirements of the IGC Code [15]:

- Design Code: Type C
- Insulation: Vacuum or Polyurethane foam

Type C tanks are containment systems with a robust design. The design of the tank scantlings and tank support is calculated and constructed to withstand liquid CO_2 sloshing at any filling level, flooding of the tank hold space, and onerous acceleration forces because of collision and grounding. They are typically of spherical, cylindrical, or bilobed pressure vessel design and are fabricated from carbon steel suitable for cryogenic service. Due to its Critical Point, the CO_2 is meant to be handled in these tanks in pressurised conditions, with the pressure maintained at around 14 to 19 bara for medium pressure conditions. To minimise the BOG rate, the tanks should be insulated with polyurethane foam or vacuum insulated for smaller volume tanks.

Type C tank should sustain a degree of internal pressure build-up due to BOG. These tanks are designed and constructed in line with pressure vessel requirements in the IGC code.

5.13 Design Principles for Bulk LCO_2 Storage

5.13.1 Onshore Storage

Land-based LCO_2 storage tanks should be adapted by following existing storage operations used by LPG export and import terminals for many years. In general, there is one main tank geometry, influenced by the storage capacity and the tank design (operating) pressure, this being vertical storage tanks with hemispherical heads. Spherical tanks may also be considered but the fabrication costs will be higher.

Vertical tanks with hemispherical heads offer superior structural integrity under pressure. The hemispherical shape distributes stress evenly across the surface, reducing the risk of structural failure and safety storage of the system.

Tanks with hemispherical heads can be designed to operate under a wider range of pressures, enhancing their versatility and suitability for different grades of LCO_2 storage needs. This flexibility allows for more precise control over the storage conditions, ensuring the quality and stability of the stored LCO_2 over time.

Furthermore, the vertical design also aids in the natural stratification of the stored LCO_2, promoting more efficient withdrawal and management of the stored product.

Typical maximum capacity is approximately 1,000 m^3. These shall be operated at ship tank's operating pressure via a BOG return line mechanism. A bulk liquid terminal storage tank of 20,000 m^3 has been assumed for the purpose of this study made up of 20 x 1,000 m^3 units. Larger individual tanks may be possible using other design types, however, the technology for LCO_2 use is less developed.

The ability of fixed storage tanks to minimise the risk of LCO_2 leakage, including large loss of containment events (LOC), is represented by the integrity level of the installation. Briefly integrity levels can be differentiated as follows:

- Double integrity level tank: In case of leakage, LCO_2 release is mitigated by a partial secondary containment, normally via a concrete pit or dike or where the roof of any outer containment tank is not gas tight. This allows a controlled release of the gas to the environment (i.e., the dike limits the spread of CO_2 over the surface and the travel distance of the gas cloud).
- Full integrity level tank: This design incorporates a full gas-tight secondary barrier such that leakage from the primary barrier does not result in the release of CO_2 into the environment. The annulus space (i.e., between the primary and secondary barrier) is vented, allowing a controlled release of gas into the atmosphere.

5.13.2 Safety of Storage Tanks

5.13.2.1 Pressure Relief Valves

PRV required by Classification Rules, IGC code (offloading vessel), ISO 21013 (fixed storage tanks) [16] and API 521 [17] should be installed for all LCO_2 tanks and inter-barrier spaces involved in offloading process, this is for both the LCO_2 receiving vessel and offloading facility.

For marine LCO_2 tanks, Class Rules, IGC code, stipulate that at least two relief valves should be fitted to each tank. These relief valves are positioned on the vapour dome (or the highest point) of each LCO_2 tank, and their discharge piping is arranged to lead to a vent in open space. Relief valves are designed, constructed, and tested to allow the maximum flow rate out of the tank under fire conditions. The accurate sizing and installation of each valve are crucial for safety as they prevent a tank from becoming liquid full before the tank pressure rise lifts the valve. As per industry guidance, it is recommended to have a remote isolation on the PSV inlet to prevent continuous depressurisation in case of the relief valve not closing. This is to prevent reaching triple point and consequent solidification of the tank content.

Type C tank relief valve may use either spring-loaded or pilot-operated safety valve. In general, such valves are fitted with a cowl arrangement that prevents the ingress of water, and coarse mesh screens mitigate the ingress of foreign objects. Implementing mesh screens should consider prevention of dry ice formation.

5.13.2.2 Pressure Management

During offloading from the ship, the pressure will fall in the ship storage tanks due to removal of liquid volume. Similarly, the pressure will start rising in the tanks being filled, due to compression of the gas present. A vapour return line between the LCO_2 receiving storage vessel and the offloading ship storage tank will ensure return of gas to the ship to equalise the pressure and ensure no emissions. In scenarios where this is not possible, LCO_2 receiving vessel or facility shall be equipped with a vaporiser to produce sufficient vapor for the ship storage tank.

While LCO_2 is being imported to or emptied from the tanks, the pressure is regulated and maintained by CO_2 vapour existing or entering via a vapour space header which is controlled by a split range pressure control system. Vapour supply during export will be provided by a vaporiser system containing electrical heaters and a knock-out drum via a branch downstream of the pumps. Difference between two systems are for vapour return line to solely operate for generated from LCO_2 tanks; this shall be implemented during offloading from ship to downstream storage facility. For vaporiser systems, these are solely operated during offload from LCO_2 tanks to third party users. Vaporiser systems are used to maintain pressure in LCO_2 tanks, where vaporised CO_2 from system shall be transferred to a vapour header.

No venting is planned at steady state. The overall CO_2 gas balance during export is maintained via CO_2 gas generated by a vaporiser to replace the volumes of LCO_2 exported from the ship-board tanks and onshore storage tanks.

When LCO_2 is offloaded from the ship, there will be a balance via the vapour return line between the onshore storage tanks and the ship, resulting in no planned emissions and prevention of over and under pressurising tanks.

If the onshore plant is shut down with no forward export for several days i.e., three to five days, heat ingress will result in pressure build up in the storage tanks, and so the BOG will need to be handled. Any venting, if finally required, is likely be penalised by the local authorities.

5.13.3 Floating CO_2 Storage

Floating CO_2storage design may follow design consideration as set out in Section 5.12 for intermediate LCO_2 receiving vessels.

Given capacity of floating CO_2 storage being 20,000 m^3, integrity levels as set out in Section 5.13 for onshore storage may be followed.

5.14 Safety Measures and Requirements

5.14.1 General

Safety remains paramount in LCO_2 offloading operations. As such, comprehensive risk assessments are recommended to be carried out prior to the offloading operation. These assessments should be conducted by all entities involved in process, which include the CO_2 capturing and offloading party as well as receiving party. These should adhere to requirements established by relevant authorities governing safety and security in the location where the offloading operation occurs.

Both the offloading facility and receiving party should commit to carrying out the LCO_2 offloading operations without venting any CO_2 gas into the atmosphere, except under emergency circumstances. As CO_2 is a greenhouse gas, its inadvertent release could contribute to climate change, adding another layer of environmental responsibility to these operations. Therefore, designing systems with maximum containment and minimum leakage should be of primary consideration.

5.14.1.1 Hazards to Personnel

Given the unique properties and potential hazards of liquid CO_2, it is crucial that personnel involved in offloading operations are adequately protected and trained. There are three levels of PPE ensembles available for use with liquefied carbon dioxide.

- Level A: This is a fully enclosed, pressurised chemical suit designed to withstand temperatures down to -78.5°C, the sublimation point of CO_2. The suit includes a large, flexible front window, integral booties, and gloves. Under gloves and booties should be worn along with a self-contained breathing apparatus (SCBA), followed by the Level A suit donned over the outside. It typically takes 15 to 20 minutes to don the Level A ensemble with assistance. In the event of a CO_2 leak, the gas can rapidly cool and form dry ice, which could cause standard Level A suits to become brittle and crack. Therefore, low-temperature Level A suits are recommended.
- Level B: This ensemble includes a chemical splash suit with a hood that seals around the SCBA face mask, with boots and gloves taped or an O-ring sealed to the suit. The SCBA is worn over the Level B suit. It can be donned without assistance in 5 to 10 minutes. This level of protection is suitable for situations where there is a risk of liquid CO_2 splash but not direct contact with dry ice or high concentrations of CO_2 gas.
- Level C: This ensemble consists of a fully equipped Hi-Vis vest worn over long trousers and long-sleeved workwear with industrial footwear. The Level C ensemble includes the following items carried in the vest:
    - Lapel-mounted personal CO_2 detector
    - Full face compact Air Purifying Respirator complete with appropriate filter
    - Insulated hood
    - LED right-angle vest-mounted flashlight
    - Safety goggles with anti-fog spray for air purification respirator (APR)
    - Elbow-length chemical safety gloves
    - Chemical break open eyewash
    - Safety glasses with side shields and face shield

- Insulated cryogenic gloves

The fully equipped Level C ensemble is comfortable and designed to be worn full-time while the individual is working in or around CO_2 equipment or facilities. Where Level A or B ensembles are available, they should be located in areas where trained personnel can easily retrieve them in a minimum amount of time and not in areas which could be considered at high risk in the event of a CO_2 leak or spill. All personnel should be issued with their own personal, fully equipped Level C ensemble, which they will each be responsible for, and to ensure they wear it at all times when on duty. All personnel must be trained in all levels of the available ensembles.

5.14.2 LCO_2 Transfer Equipment and Components

Choosing the appropriate transfer equipment for LCO_2 offloading operations requires considerable attention.

Before the deployment of any equipment, it is crucial to thoroughly evaluate all components of the offloading system. This includes the loadings on manifold working platforms, presentation flange, hoses, support arrangements, "Y" reducers, and any emergency release couplings (ERC) along with their operating systems. These components must be certified and proven to be suitable for this specific application.

The process of technology qualification should mirror the one used by Classification/Certification authorities for the approval of the offloading system and its integration on-board an LCO_2 offloading vessel.

In scenarios where for offloading, rigid marine articulating arms or flexible hoses are used, these can be provided by the manufacturer. It is crucial that entity responsible for offloading LCO_2 continuously monitors and controls the integrity and safety of the offloading system during operation.

A LCO_2 supply transfer system is optional and for an LCO_2 offloading vessel this might be configured as follows:

- A rigid marine articulating arm system incorporating a quick connect /disconnect coupler (QC/DC) and an emergency release system (ERS).
- A fully supported and protected LCO_2 flexible hose system with an ESD link, QC/DC, and ERS. A dry break away coupling that combines the functions of a QC/DC and ERS or any similar connection and safe release devices will be acceptable if it complies with the principles of ISO 2928/ISO 21012/EN 13765 and is acceptable to the authorities.
- The flexible hose should comply with ISO 2928/ISO 21012/EN 13765. Any deviation from these standards should be acceptable to the authorities.

5.14.3 LCO_2 Boil-Off Gas Management Equipment

BOG, which is generated by heat ingress and primarily by the vapour returning from a warm LCO_2 tank during offloading, necessitates continuous management or extraction from the LCO_2 storage tank.

Adequate provisions should be made for the control and management of the BOG generated during offloading, without release to the atmosphere. Considerations include:

1. Offloading transfer parameters should be tailored and adjusting during offloading to minimise and control the production of BOG and/or displaced gas in the receiving tank(s).
2. The most relevant factors that will affect the amount of BOG generated during a typical offloading operation are:
   a. Cool-down of the transfer system and offloading line (this can generate large quantities of BOG but has a short-term effect)
   b. Different conditions in the offloading facility tanks and the receiving tanks (in particular, the temperature of the receiving tank can have long-lasting effects on BOG production during the whole transfer)
   c. Transfer rates (ramp-up, full flow, ramp-down/topping-up)
   d. Heat gain in the pipeline and transfer equipment between the offloading facility's tank and the receiving facility's tank
   e. Pumping energy
3. During the preparation stage the maximum tank pressures should be agreed to prevent any inadvertent gas release to the atmosphere.
4. The agreed BOG management strategy and procedures need to be defined in the operating procedures. This may be done by any of these means, individually or in a combination:
   a. Allowing pressure to build up in one or both systems
   b. Cooling the vapour space to control/collapse the pressure by using LCO_2 top-filling lines in the receiving tank
   c. Returning gas to the offloading facility via a vapour return line
   d. Liquefaction of gas with a reliquefaction system.

Even though the BOG return from offloading operations is temporary, it can be considerable, given the size of the tank being offloaded, its saturated temperature, and the filling level before offloading. The use of a vapour return line during offloading can facilitate BOG management between supplier and receiver and help to control and maintain the correct pressure in the receiving tank(s). Furthermore, using a vapour line can provide a further benefit in reducing the time for the whole offloading operation, so this may be considered when offloading has stringent time constraints.

To manage this, sizing of the vapour return line should account for maximum possible BOG flowrate during operations that is dependent on tank size, CO_2 saturation temperature and filling level which will prevent overpressure scenarios.

Based on specified pressure conditions for LCO_2 storage and offloading, corresponding BOG will be at appropriate temperatures as per pressure conditions. LCO_2 at these conditions exists close to the liquid-gas boundary, therefore if pressure of LCO_2 drops below operating limit and close to induce liquid-gas phase change, the resulting vapour will need to be managed using compressors, re-condensers and reliquefaction systems.

5.14.3.1 Re-Condensers (Liquefaction of BOG)

Re-condensers are specialised shell and tube heat exchangers that are integral to the BOG management system of large LCO_2 offloading facilities, such as fixed storage tanks and offloading vessels. A re-condenser functions by cooling the BOG (vapour) using a refrigerant, which can be provided through an integrated refrigeration system. Possessing a large re-condenser is beneficial not only for offloading larger storage capacity ships but also for managing the natural boil-off from sizable LCO_2 tanks. However, complexities of handling multi-product systems will need to be considered to ensure these are segregated.

For all heat exchangers, both sides shall have the same maximum design temperature determined by the hottest of the fluids on either side. For upset conditions, overpressure of connected piping at resulting upset temperature may be acceptable if permitted by relevant piping design code.

5.14.3.2 Reliquefaction System

The type of reliquefaction plant may be a mixed refrigerant plant. In this type of reliquefaction system, BOG is cooled by a single refrigeration circuit that uses a mixture of refrigerants. The cooling rate of the BOG is controlled by optimising the refrigerant mixture and the number of heat exchangers used (i.e., multiple parallel heat exchangers to accommodate capacity). As this type of reliquefaction plant uses a single refrigeration circuit, there are fewer compressors compared to the cascade system, reducing the size and cost of the system.

5.14.3.3 Compressor

A compressor should be specified and implemented on the vapour return line for storage and offloading at different conditions, particularly from onshore low pressure conditions to on-board medium pressure conditions. Compressor may only be specified here if the operation is at two distinct pressure conditions.

This may be a centrifugal compressor in order to handle large volumes of gas and less prone to wear and tear for continuous operation. Compressor should be capable of achieving necessary pressure increase to conform with pressure conditions of on-board storage tank.

5.14.4 Emergency Shutdown Valves (Remotely Operated Isolation Valves)

ESD valves, typically of globe or gate valve design, should be strategically placed at several locations within the LCO_2 transfer system of both the offloading facility and the receiving facility. At the very least, two ESD valves are necessary to isolate the offloading piping system at both ends (i.e., the offloading facility and LCO_2 receiving vessel). These valves, which can be operated remotely, are designed with either pneumatic or electro-hydraulic safe-closed activation mechanisms.

5.14.5 Emergency Shutdown System (ESD)

ESD systems play a pivotal role. Their purpose is to ensure a dependable, swift, and secure shutdown of LCO_2 systems when faced with unexpected or emergency situations.

The ESD system serves as a key element of the safety system, designed to curb the damage, reduce inventory loss and prevent the escalation of a single fault or failure during offloading. This is achieved by either manually or automatically halting and carefully transitioning the transfer operation to a safe and isolated state.

The ESD should be capable of being triggered from either side of the offloading transfer system, that is, the LCO_2 offloading vessel or the LCO_2 receiving vessel/facility. Both systems should be designed to shut down simultaneously. The offloading vessel should be compatible with various link ESD systems. Common link ESD systems include:

- Optical Fibre System: This involves an optical fibre cable originating from the LCO_2 offloading vessel, which connects to the LCO_2 receiving vessel/facility using a plug-in socket located at the manifold.
- Pneumatic Link: This system uses a hose pressurised with air from the offloading vessel, which operates an onboard pressure switch. A loss of air pressure due to venting the line or activation of a solenoid valve onboard or hose parting will trigger the pressure switch, initiating the ESD.

- Electric Link: This system uses flame-proof connectors to connect the LCO_2 supplier cable to the LCO_2 receiving vessel interface. It employs a combination of digital 4-20 mA analogue signals.

Typically, there are two ESD levels, ESD-1 and ESD-2. Both systems are optional for comprehensive safety. ESD-1 should lead to the controlled shutdown of LCO_2 offloading pumps, LCO_2 pressurisation equipment, and the closure of the ESD valves (within 30 seconds). ESD-2 should result in the disconnection of the loading arm or flexible hose. The ERS should be designed to minimise the release of LCO_2 and to protect the LCO_2 transfer arm/hose through safe disconnection. The ERS design should include an ERC with interlocked isolation valves to minimise the LCO_2 release when the ERS is activated.

The activation of the ERS should lead to the simultaneous closure of the interlocked ERC isolation valves, followed by the separation of the ERC and the withdrawal of the LCO_2 transfer arm from the LCO_2 receiving vessel's manifold and structure. These actions are designed to prevent damage to the LCO_2 transfer arm and uncontrolled spillage of LCO_2.

The ESD system should be designed to safely halt and isolate the offloading of LCO_2 to the receiving vessel. The ESD systems should meet the minimum functional requirements as per relevant international standards, such as those specified by SIGTTO Recommendations for Emergency Shutdown and Related Safety Systems [18], with necessary adaptations for LCO_2 offloading operations.

5.14.6 Emergency Release System (ERS)

For secure offloading operations, each transfer line must be equipped with a single automatic and/or manually activated ERS that incorporates an ERC.

The following ERS specification requirements should be considered as a minimum:

- The ERS should be designed with a double seal and leak prevention arrangement with visual indication at the break point.
- The ERS operating system should retain enough stored power to release all transfer hoses in the event of a blackout on the ship and the non-availability of ship-provided utilities.
- The ERS design should be capable of operating and releasing the system when exposed to the maximum theoretical LCO_2 flow rate.
- The ERS system should be capable of manual activation from a remote safe location where the offloading process is monitored on-board the offloading vessel.
- Clear step-by-step activation procedures should be posted at the ERS operating location.
- The control/safety system should initiate an ESD-1 with a trip signal to both vessels prior to activation of the ERS and offloading system disconnection (ESD-2).
- In the event of the vessels breaking away (exceeding operating envelope), the ERS must automatically operate and release the transfer system.
- The design of the ERS should comply with guidance documents, such as SIGTTO Recommendation for Emergency Shutdown and Related Safety Systems, adapted as necessary for LCO_2 offloading operations.

The ERS should be designed as one of the following:

- Two ERC valves mechanically interlocked and operated simultaneously by a single actuator. This action is to enable the activation of the ERC.

- Two ERC valves to be operated independently of the ESD, by two interlocked actuators. Design arrangements should be provided to prevent the opening of the ERC. When separated, the valves should remain safely closed even in case of hydraulic or electric power failure. An electric, hydraulic, or mechanical system should be provided to prevent reopening of the valves before reassembly of the ERS after disconnection.

Alternative designs that comply with the safety principles of relevant standards may be considered provided they carry appropriate Certification/Classification approvals.

The ERS should be designed to ensure that the ERS is active only during LCO_2 transfer and testing. A manually operated hydraulic valve should be installed on the hydraulic supply line to secure it when the arm is not connected to the LCO_2 receiving vessel's manifold.

5.15 References

[1] International Organization for Standardization, “ISO 10418:2019 Petroleum and natural gas industries Offshore production installations - Process safety systems,” International Organization for Standardization, 2019.

[2] American Petroleum Institute, “API RP 14 C Recommended Practice for Analysis, Design, Installation, and Testing of Basic Surface Safety Systems for Offshore Production Platforms.,” American Petroleum Institute, 2007.

[3] Norsok, “Norsok Standard - Process Design,” Standards Norway, 2006.

[4] International Electrotechnical Commission, “IEC 61508-1:2010 Functional safety of electrical/electronic/programmable electronic safety-related systems - Part 1: General requirements. International Electrotechnical Commission.,” International Electrotechnical Commission, 2010.

[5] International Electrotechnical Commission, “IEC 61511-1:2016 Functional safety - Safety instrumented systems for the process industry sector - Part 1: Framework, definitions, system, hardware and application programming requirements. International Electrotechnical Commission.,” International Electrotechnical Commission, 2016.

[6] Endress+Hauser Presentation for GCMD, “Liquid CO_2 (LCO_2) Offloading Solution – Storage and Transfer,” 2023.

[7] Emerson Automation Solutions Report for GCMD, “Part D1: LCO_2 Quantity and Quality Measurement,” 2023.

[8] OSHA, “Carbon Dioxide - Occupational Safety and Health Administration Occupational Safety and Health Administration,” OSHA, 2022.

[9] International Organization for Standardization, “ISO 21012:2018 Cryogenic vessels — Hoses,” International Organization for Standardization, 2018.

[10] British Standards Institution, “BS 4089 Specification for Metallic Hose Assemblies for Liquid Petroleum Gases and Liquefied Natural Gases,” British Standards Institution, 2017.

[11] British Standard, “BS EN 13765:2018 Thermoplastic multi-layer (non-vulcanized) hoses and hose assemblies for the transfer of hydrocarbons, solvents and chemicals. Specification,” British Standard, 2018.

[12] OCIMF, Recommendations for Liquefied Gas Carriers Manifolds, OCIMF, 2018.

[13] DNV, “DNV-RP-F104 Design and operation of carbon dioxide pipelines,” DNV, 2021.

[14] British Standards Institution, “PD 8010-1 Pipeline systems. Steel pipelines on land. Code of practice,” British Standards Instituion, 2016.

[15] International Maritime Organization, International code for the construction and equipment of ships carrying liquefied gases in bulk, International Maritime Organization, 1993.

[16] International Organization for Standardization, “ISO 21013-1:2021 Cryogenic vessels — Pressure-relief accessories for cryogenic service — Part 1: Reclosable pressure-relief valves,” International Organization for Standardization, 2021.

[17] American Petroleum Institute, “API Standard 521 Pressure-relieving and Depressuring Systems,” American Petroleum Institute, 2014.

[18] SIGTTO, ESD Systems Recommendations for Emergency Shutdown and Related Safety Systems, Witherby Seamanship, 2021.

6. Procedures for Offloading Liquid CO_2

This chapter outlines the operating procedures and the necessary steps in the LCO_2 offloading operation with focus on minimising risks and optimising performance. Safety measures are incorporated in the procedures and environmental protection measures have been enumerated. Responsibilities of personnel involved in offloading operations have been outlined. The chapter ends with emergency response procedures for LCO_2 release and examples of typical emergency responses have been provided.

6.1 General

6.1.1 LCO_2 Offloading Plan

A LCO_2 offloading plan should be established to ensure that the offloading operations are executed effectively and safely. This plan should illustrate and document compliance with relevant authorities' regulations, corporate requirements, and the vessel(s)'s Safety Management System (SMS) requirements.

The LCO_2 offloading plan should include, but not be limited to, the following:

- Purposes;
- Safety policy and objectives;
- Organisational planning;
- Operations (to include simultaneous operations or SIMOPS, if applicable);
- Procedures and checklists;
- Risk management;
- Management of change;
- Emergency response;
- Training; and
- Communication during LCO_2 offloading operations.

The documentation required by the SMS of both entities should be available for the LCO_2 transfer, including the SDS of the LCO_2 and offloading procedures and checklists. It is essential that this documentation is readily accessible, serving as a guide for the operation and acting as a resource in case of any uncertainties or emergencies.

6.1.2 Risk Assessment

A risk assessment should be carried out by the LCO_2 receiver or terminal operator and the offloading ship (offloading facility), taking into account recognized standards such as IEC 31010 [1], DNV-RP-F104 [2], ISO 27913 [3] and ISO 17776 [4]. The specific risk assessment should be revisited whenever the conditions of the study scenario during the risk assessment change, such as:

- Different offloading ships;
- Different offloading systems;

- Different locations;
- Modifications of operating procedures;
- Introduction of simultaneous operations; and/or
- Modifications to offloading equipment.

Periodic reviews should be conducted to identify potential hazards and associated risks, which may highlight the need for additional or revised risk assessments.

The risk assessment should be reviewed and revised (as needed):

- At least once every three years; or
- Upon the occurrence of incidents and/or accidents as a result of exposure to a hazard; or
- Where there is a significant change in work practices or procedures.

By continuously re-evaluating risks and adjusting procedures as necessary, operations remain as safe and effective as possible in the dynamic environment of LCO_2 offloading.

6.1.3 Responsibility of Offloading Stakeholders

6.1.3.1 Person In Charge (PIC)

The PIC is an individual that should be appointed by the LCO_2 receiver to be responsible for the offloading and transfer of LCO_2 and the associated offloading documentation. For ship-to-ship transfers, the PIC may also be the Master of the offloading ship.

The identity of the PIC should be communicated to all parties involved in the offloading operation before the offloading begins. The PIC is responsible for ensuring that agreed upon offloading procedures are followed and that operations align with all applicable regulatory requirements.

The responsibilities of the PIC include the following:

- Initiating and concluding the offloading;
- Ensuring that all required communications are made with the Implementing Authority;
- Ensuring completion of inspection forms and checklists;
- Confirming with the Master(s), or his/her representative, the correct relative location of vessels, mooring, and placement of fenders;
- Conducting a pre-operation meeting with the responsible personnel from the receiver;
- Assessing current and forecasted meteorological conditions for the duration of the operations;
- Monitoring communications throughout the operations;
- Reviewing and ensuring that site-specific risk mitigations are in place, including monitoring and safety zones;

- Ensuring that the transfer system is in good order and that the emergency shutdown system is properly connected and tested;
- Ensuring the safe connection/disconnection of the transfer system and associated emergency release systems;
- Confirming that SIMOPS assessment has been carried out, where applicable;
- Monitoring LCO_2 transfer rates and pressure management;
- Advising the Master or his/her representative when offloading is completed; and
- Ensuring that, when necessary, all incidents are reported without delay and by the most direct means to the Implementing Authority and Port Master, and that a full written report of the circumstances of the incident or occurrence is submitted to the Port Master as required.

In this critical role, the PIC serves as the lead of the offloading process, coordinating multiple aspects to ensure that the operation proceeds safely, efficiently, and in compliance with all regulations and procedures.

6.1.3.2 Master (LCO_2 Receiving Vessel)

It is important to note that the master of the LCO_2 receiving vessel should retain control over his/her vessel. The master must also ensure that the LCO_2 offloading operation is conducted safely. The master will appoint a responsible officer to manage the LCO_2 offloading operations onboard and to liaise with the PIC. The master is also responsible for informing the PIC of any changes to pre-agreed SIMOPS activities onboard the LCO_2 receiving vessel.

6.1.4 Communication

6.1.4.1 Communications between Vessel and Offloading Facility

At least two reliable and independent means of communication should be available at all times during LCO_2 offloading operations. No transfer operations should begin until effective communication has been confirmed by all parties. In the event of a communication failure, all offloading operations should be immediately suspended and not resumed until effective communication has been re-established.

6.1.4.2 Non-verbal Communications

Equipment for non-verbal communication should be robust and reliable. Hand signals for communication can also be established and agreed between the parties before offloading begins.

6.1.5 Controlled Zones

6.1.5.1 Determination of Safety Zone

The safety zone, which is predetermined, should be enforced before the LCO_2 transfer system is connected. This can be achieved by:

- Allowing access only to personnel designated for offloading.
- Minimising the risk of dropped objects by temporarily halting operations of cranes, forklifts, and stackers.

- Temporarily eliminating collision risks by limiting vehicular access, port mobile equipment, and passing vessels.
- Checking the readiness of hazard prevention and mitigation measures, such as gas detection systems.

6.1.5.2 Determination of Security Zone

A reasonable buffer distance (i.e., a few meters) should be set up between the safety zone and the adjacent port location to ensure public safety and a secure working environment for offloading personnel. The establishment of the security zone involves:

- Marking the area with reflective paint, cones, and other materials that are highly visible under all anticipated offloading conditions, including at night and during bad weather.
- Assigning personnel to monitor the area, especially if simultaneous operations like passenger embarkation/disembarkation are planned, to effectively direct the public away from the safety zone.
- Implementing temporary speed restrictions for vehicles moving in traffic lanes close to the security zone.

6.1.5.3 Determination of Marine Zone

Marine zones are specific to each port, and their enforcement should be handled by the port authority either through physical signals or communication procedures, to prevent other ships from navigating close to the offloading operation.

6.2 Procedures for LCO_2 Offloading

6.2.1 General

6.2.1.1 Planning phase

Compatibility, Interface Review and Notification of Authorities

The assets involved in the offloading of LCO_2 (such as the ship, loading arm, flexible hose, and piping from the fixed CO_2 storage) should have clear specifications regarding the type, size, and category of LCO_2 receiving vessels they can safely and efficiently transfer LCO_2 to.

Before agreeing to execute a planned offloading operation, a compatibility review should be performed. This review should consider various physical interfaces, including piping/hose manifold connections, and software elements like offloading control software and safety systems that exist between the offloading asset and the receiving vessel. Key physical parameters to be confirmed include the arrival draught, freeboard, the height of the offloading station above the waterline, and the height difference between manifolds during discharge. The height data is crucial as it can influence the offloading asset's ability to perform the operation, particularly if a marine loading arm is employed. The use of flexible hoses can accommodate a wider range of manifold height differences, depending on the design of the supporting structure, such as a crane.

Once the compatibility and interfaces between the offloading facility organisation (OFO) and the receiving operator (RO) are agreed upon, the local port authorities should be informed. By giving the port authority notice in advance, they can ensure that the necessary personnel are available, ranging from conducting audits of license holders to identifying local emergency services that can be on standby in case of emergencies.

6.2.2 Ship-to-Ship and Ship-to-Shore

6.2.2.1 Mooring LCO_2 Receiving Vessel and Establishing Control Zones

The mooring setup should firmly secure the LCO_2 receiving vessel to a dock or at anchorage so that components of the LCO_2 offloading system, such as couplings, hoses, support structures, and loading arms, are not negatively affected by relative movements due to weather conditions or changes in draft during the offloading process. Relevant standards and guidelines for mooring arrangements and their impact on offloading operations can be found in ISO 19901-7 [5], ISO 16904 [6], and best practice guidelines from OCIMF publications, specifically within "OCIMF Mooring Load Analysis during Ship-to-Ship Transfer Operations" [7], and "OCIMF Mooring Equipment Guidelines" (MEG4) 2018 .

Before the commencement of LCO_2 offloading, three control zones should be defined and maintained:

Safety Zone
The safety zone, which is predetermined, should be enforced before the LCO_2 transfer system is connected. This can be achieved by:

- Allowing access only to personnel designated for offloading.
- Minimising the risk of dropped objects by temporarily halting operations of cranes, forklifts, and stackers.
- Temporarily eliminating collision risks by limiting vehicular access, port mobile equipment, and passing vessels.
- Checking the readiness of hazard prevention and mitigation measures, such as gas detection systems.

Security Zone
A reasonable buffer distance (i.e., a few meters) should be set up between the safety zone and the adjacent port location to ensure public safety and a secure working environment for offloading personnel. The establishment of the security zone involves:

- Marking the area with reflective paint, cones, and other materials that are highly visible under all anticipated offloading conditions, including at night and during bad weather.
- Assigning personnel to monitor the area, especially if simultaneous operations like passenger embarkation/disembarkation are planned, to effectively direct the public away from the safety zone.
- Implementing temporary speed restrictions for vehicles moving in traffic lanes close to the security zone.

Marine Zone
Marine zones are specific to each port, and their enforcement should be handled by the port authority either through physical signals or communication procedures, to prevent other ships from navigating close to the offloading operation.

6.2.2.2 Pre-offload

Pre-Offload Operational Meeting and Safety Checks

Before the offloading operation begins, a pre-operation review meeting should be held. This meeting should involve all key parties, including the PIC from the offloading supplier, the PIC from the LCO_2 receiving vessel, and when necessary, the terminal representative. The purpose of this meeting should be to agree on the specifics of the offloading operation. This includes procedures and operational parameters related to the manifold connection, dry coupling, emergency release, and flow rates for each stage of offloading (cool down, ramp-up, full-flow, and topping up to the filling limit), as well as any potential limitations.

If SIMOPs within the control zone (which includes the safety zone and security zone) are planned, it is crucial that personnel responsible for these parallel activities are given clear instructions. This includes safety precautions, emergency response procedures, and the establishment of a common communication channel for receiving emergency instructions.

Finally, a thorough inventory check and functionality test should be conducted for all PPE, cryogenic protection, and monitoring components to ensure they are ready for the offloading operation. Specific checklists for the planned offloading operation and any SIMOPs should be completed and retained for record-keeping purposes.

Completing the Offloading Connection

The type of receiving asset used (i.e., a LCO_2 receiving vessel, floating CO_2 storage, or piping from a fixed storage tank) can determine the number of pipe/hose connections for liquid and vapor, as well as the interfaces for offloading control, including the ESD system.

Hose handling equipment, such as cranes and supporting structures, or fixed pipe loading arms, should be properly positioned to enable easy connections and ensure a safe disconnection in the event of an ERS activation. To prevent phase change of LCO_2, piping and flanges that are insulated should be connected to the LCO_2 receiving vessel.

For the offloading control and ESD systems, there can be a variety of interfaces and connections. These can range from older systems like pneumatic link systems to more modern ones that use electric-based links (examples include SIGTTO and Miyaki, Pyle National.) and fibre optic connections.

ESD Testing

Before commencing the offloading operations, both parties should routinely check the functionality of their ESD systems. This involves the following assessments:

- The operational readiness of the emergency release system, including its mechanical, hydraulic, and electrical release mechanisms, should be confirmed.
- Dry connect/disconnect couplings should undergo a visual inspection and testing.
- The ESD system, including its safety logic, should be tested and confirmed to be operational.
- The completion and results of these tests should be documented and made accessible for port authority audits.

Any anomalies or defects identified during the tests should be promptly reported to the PIC for evaluation before proceeding with the offloading of LCO_2.

6.2.2.3 LCO_2 Transfer

Drying LCO_2 Piping

Prior to the commencement of the LCO_2 offload, the corresponding piping system shall be dried to ensure there is no water content within pipework that will result in formation of carbonic acid when in contact with LCO_2. The piping system that needs to be dried shall be isolated which is done by closing corresponding valves that would prevent flow of LCO_2 during offloading. Once isolated, piping system shall be depressurised. This can be done by slowly opening a specific valve for depressurising located on the piping system. The corresponding pressure gauge shall be monitored to ensure pressure is decreasing at a safe rate. Once piping system has been depressurised, drying step can begin. This shall be done by introducing a dry gas, such as dry nitrogen or dry air into the piping system. The dry gas shall be introduced at one end of the pipeline and vented out at the other end. The drying process shall continue until the humidity level in the piping system is within acceptable limits, a target in industrial applications is to reduce the humidity level to a dew point of -40 °C or lower. Following drying, piping system shall be pressure tested to ensure that it is safe to use.

Cooling Down and Ramping up LCO_2 Offload Flow

In most cases, LCO_2 receiving vessel/storage terminal conditioning might be done prior to LCO_2 offload from merchant ships. If respective LCO_2 equipment are not pre-conditioned, the following steps may be required.

The LCO_2 receiving vessel/storage terminal might initiate a pre-cooling process for some of the LCO_2 offloading piping and the LCO_2 tank. For this process, required CO_2 shall be introduced via dedicated inventory pre-located onboard ships or storage facilities. Once the system is connected, CO_2 vapour will be gradually introduced into the offloading piping until thermal equilibrium is achieved. This means that the LCO_2 piping, the manifold, and the hoses will reach a temperature of -20 to -35°C, as indicated by the manifold's temperature gauges.

It's crucial to note that the cooldown process should be carried out in stages, with vapour slowly introduced into the LCO_2 pipe. Repeated sudden cooldowns of the LCO_2 pipes, hoses, and valves can lead to excessive thermal stresses, which can cause fatigue damage and cracks. Once the entire connected LCO_2 transfer system reaches a temperature of -35°C or lower, up to -55°C, the LCO_2 transfer from the merchant ship can be gradually increased to the desired flow capacity. Before commencing the LCO_2 discharge it is critical to ensure that pipelines are pressurised above CO_2 triple point to prevent dry ice formation within the piping.

Initially, the receiving LCO_2 tank will be filled using the top spray connection to reduce the remaining vapour in the tank and achieve a further cooling effect as seen in Figure 6.1. When the receiving tank temperature nears -35°C, the LCO_2 transfer can be elevated to the agreed-upon rate. It is crucial that during offload of LCO_2, pressure is always maintained above the triple point.

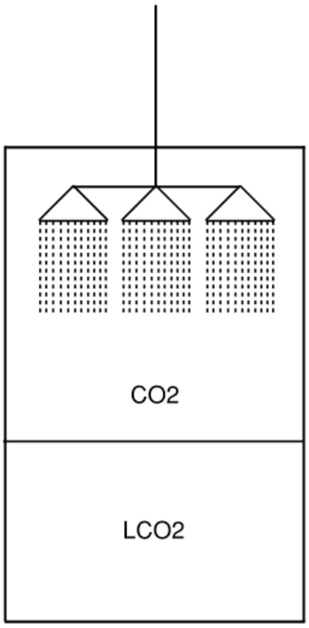


Figure 6.1 – Schematic of LCO_2 top spray connection filling

Throughout the entire cooldown and ramp-up of the LCO_2 transfer rate, special precautions are necessary to prevent the release of gas vapours into the atmosphere. Vapour management techniques will include:

- The use of a dedicated vapour line to return the BOG to the offloading facility.
- BOG management strategies, such as PBUs, to maintain pressure in LCO_2 storage tanks.

Slowing Down LCO_2 Transfer, Topping-up to Loading Limit (Filling Limit)

Each receiving tank has a specific loading limit and filling limit that must not be exceeded during offloading which are to be monitored by each tank's level transmitter that are connected to a dedicated alarm system. While there are no industry codes that specify filling limits for LCO_2 tanks, the IGC code sets the filling limit at no more than 98% at the reference temperature, and other studies suggest a lower limit for high-pressure conditions for LCO_2. The corresponding loading limit is calculated based on the ratio of the relative density of LCO_2 at the reference temperature (i.e., the relief conditions of the tank) and its relative density during offloading. It is crucial that filling limits and loading limits are specified independently.

The loading limit is not a fixed value, but rather a curve that describes the ratio of the LCO_2 density at relief condition versus the density of fresh LCO_2 during offloading. This means that the loading limit accounts for the expansion effect (increase in volume) of the CO_2 should the tank be exposed to heat ingress, thereby minimising the possibility of CO_2 being vented through the relief valve.

If a tank accidentally exceeds its loading limit curve during LCO_2 offloading, it must be reduced back to the loading limit to avoid the potential of two-phase flow being ejected from the tank vent mast in the event of heat ingress. After each offloading operation, the final loaded condition of the tank should be reported, along with a copy of the loading curve, and made available to the port authority.

6.2.2.4 Post LCO_2 Transfer

Draining and Stripping of LCO_2 and Vapour Transfer Lines

Upon completion of the offloading operation, all LCO_2 transfer piping and hoses should be thoroughly drained and stripped to remove any remaining pockets of LCO_2. Any residual LCO_2 left in the piping can lead to pressure build-up, as the ambient environment warms up the LCO_2, resulting in volumetric expansion. During drainage, it is critical to maintain pressure within transfer lines above CO_2 triple point conditions until all liquid is removed.

Residual LCO_2 in the liquid line and CO_2 in vapour line should ideally be collected to minimise environmental impact by purging the lines by dry air or nitrogen. Specific method for handling residual LCO_2 and CO_2 will depend on available facilities and environmental regulations in place. Exact volume of residual LCO_2 and CO_2 may vary depending on size and length of transfer piping and hoses and amount of LCO_2 transferred. Volume of residual LCO_2 and CO_2 may be up to 0.05% of volume of total LCO_2 offloaded.

Completion, Disconnection and Stowage of LCO_2 Offloading Connections

The disconnection process starts with the liquid and vapour piping and hoses used for offloading. The dry disconnect coupling that links the piping or hoses should be activated first, followed by the disconnection of the interfaces for offloading control, including the emergency shutdown system.

Subsequently, all hose handling equipment (such as cranes and supporting infrastructure) or fixed loading arms should be disengaged and moved clear of the LCO_2 receiving vessel. The dry connect/disconnect coupling, emergency release coupling, and ESD interfaces should be handled with care to avoid mechanical damage from accidental drops.

Closing and Preparation of Next LCO_2 Transfer

Given the potential variability of LCO_2 offloaded and intermittency in flows, the effects of repeated pressure cycling should be considered, particularly at ports, where equipment will not be operating continuously.

At the end of the offloading, system should be depressurised to remove any residual LCO_2, to prevent formation of dry ice in the system, resulting in blockages or damage. System should be thoroughly inspected for any signs of wear and tear or damage, and any necessary maintenance or repairs should be carried out before the next transfer.

Before the next offloading, system should be carefully pressurised and integrity of all seals and connections should be checked. Equipment should be pre-cooled before introduction of LCO_2 to prevent thermal shock. In addition, safety systems should be operational and ready to handle high pressures and low temperatures associated with LCO_2 offloading.

Post-offload Review and Reporting

In addition to reaching an agreement on the quality and quantity of the offloaded LCO_2, all incidents related to the offloading process should be meticulously recorded. This includes any noncompliance with protocols, miscommunication, and failure of any components. These records are crucial for maintaining transparency, improving future operations, and ensuring safety standards. All such incidents should be promptly reported to the port authority for their review and necessary action.

6.2.3 ISO Tank Containers (Cassette)

The following offloading procedure is applicable to the offloading of LCO_2 ISO tank containers (cassette) from container ships:

6.2.3.1 Lift Planning

a. Risk Assessment: Conduct a thorough risk assessment for the lifting operation. This should include a lift plan or lift study, and a safe work method statement (SWMS) if required by local regulations.

b. Lift Plan: Determine the need for a lift plan. The need for a lift plan depends on the level of risk and complexity of the lift. Additional endorsement by a lift engineering specialist or additional authorisation by the entity "lifting authority" may be required, depending on the category of Lift.

c. Approval: Ensure that the lift is safe to execute, with mitigations for all identified risks and hazards, and is in accordance with legislative requirements for the lifting operation.

d. Endorsement: Obtain verification by a lift engineering specialist or competent delegate that the engineering lift study is safe to execute. It should mitigate all identified risks and hazards, provide a safe system of work, be in accordance with legislative requirements for the lifting operation, and that all required technical support has been provided and incorporated.

e. Additional Authorisation: Verify that the lift has been correctly categorised, that the lift plan has been developed, that the correct management processes have been followed during the applicable approval and endorsement stages and has adequately considered and mitigated all identified personal safety and process safety risks.

f. Documented Lift Plan: If required, the lift plan should include the following:

- Assessment of the lifting task, including load rigging and handling arrangements, load manoeuvring, load integrity and stability, pick up and set down arrangements, ground bearing capacity, and simultaneous operations.
- Assessment of overall lifting conditions, including the adjacent live equipment, worksite environment, ground and weather conditions, load rigging method and handling arrangements, lift area barrier management and warning signage.
- Clearly defined roles and responsibilities of personnel involved in the lifting operation.
- Details of the lifting capacities specific to the crane and rigging configuration.

6.2.3.2 Equipment Readiness

a. Pre-shift inspection and functional tests: The crane operator shall carry out a visual inspection and functional tests before the start of each work shift. The inspection should include:

- All relevant items indicated in the operations manual.
- Operating and emergency controls.
- Brakes.
- Safety switches and interlocks, including limiting and indicating devices.
- Visual inspection of the structure of the crane.

- Wire ropes to ensure they are on the drum, correctly reeved on the sheave, and are not damaged or excessively worn.
- The results of these inspections and tests should be recorded in a logbook and kept with the crane.

b. Pre-Lift Checks: Prior to commencing a lift, the following shall be performed:

- An inspection of the ISO tank containers to ensure these are properly isolated and disconnected from all associated piping systems, containers are secured and lifting points are in good condition.
- Pre-use checks for all lifting equipment in accordance with regulatory requirements, national standards, and applicable industry practices to confirm it is fit for purpose. All lifting equipment including slings and hooks shall be visually inspected prior to each use and periodically inspected for damage and wear by a competent person with inspection records kept. All auxiliary lifting equipment should be tagged or otherwise physically identified (e.g., plate on spreader beam) with the date of the lifting equipment's last inspection and shall be done so to certify equipment in accordance with regulatory requirements in jurisdictions where these exist. Documented maintenance records for the lifting equipment shall be available.
- A visual inspection of the associated environmental and operational conditions in which the crane is intended to be installed, erected, and used.

6.2.3.3 Competence of Personnel

a. Personnel training and certification: All personnel involved in lifting operations shall be trained and certified in accordance with local regulations as applicable to the lift and its location.

b. Operator familiarity and competence: Operators of lifting appliances shall be familiar with and competent in the operation of the StS crane that they are required to operate. This includes understanding the design, layout, operating functions, and maintenance and inspection requirements of the appliance.

c. Training and qualification for crane operation, rigging, and inspection: All persons either operating, rigging, or inspecting cranes and auxiliary equipment shall be trained and qualified for the particular discipline and meet all regulatory competency requirements for the jurisdiction that the task is undertaken.

6.2.3.4 Lift Execution

a. Isolation of Personnel: The isolation of personnel from lifting operations shall be considered in the risk assessment for the task. Workforce members who are not involved with the lift shall be restricted from the lift zone through effective barrier management. Personnel shall not place themselves under a suspended load or in the line of fire of the load. Forklifts shall not be used without the operating area being segregated for pedestrians or warning signs are in place.

b. Communication: Radios shall be used for blind lifts as the primary means of communication and as an emergency means of communications.

c. Tag Lines: Tag lines shall be made of non-conductive material. Lifting gear shall not be used as tag lines.

d. Lifting Points and Structures: Lifting points on new structures that are certified by a competent engineer shall be supported by weld inspection and non-destructive testing (NDT). Lifting from uncertified steel structures (such as scaffolding, or pipe work) shall only be performed after approval from a competent person.

e. Wind speed monitoring: If the crane being used for a higher risk critical lift does not have an anemometer then a safety observer/ spotter, located at the highest viable elevation, shall monitor the wind speeds with a device to confirm compliance with the operating limits for the lift.

6.2.3.5 Loading/Unloading of ISO Tank Container

Once the ISO tank container has been lifted and loaded on a LCO_2 road tanker, it is transported to a storage facility where LCO_2 will be offloaded from ISO tank to a final destination. The following section details a proposed LCO_2 unloading procedure for the discharge of LCO_2 from ISO tank container to bulk storage facility.

General

During the process of loading and unloading road tankers, it is crucial to adhere to the following general safety guidelines, in addition to the specific operating instructions for the equipment utilised by the organisation:

- Tanker placement: ensure it's in an open space; and keep it as level as possible.
- The tanker should be positioned in a way that allows for easy departure.
- Immediately after halting the tanker and its engine, the wheel chocks should be secured.
- An inspection of the stationary bulk tank and its accessories as per the checklist should be conducted.
- If the pressure of the stationary tank falls below minimum allowable pressure, the receiving facility operator and authorities should be notified. The unloading process should not continue/commence.
- Verify that there are no major defects in this equipment that could disrupt the standard unloading process, specifically:
  - Safety devices obstructed by ice;
  - Malfunctioning control equipment, such as pressure gauges, level controls, or weighing machines;
  - Significant leakage of carbon dioxide gas or liquid: Any major defect should be reported and guidance sought before initiating the unloading. Minor defects should be reported and documented for potential future action.
- Any minor defect should be reported and documented for potential future action.
- If applicable, ensure that the hydraulic connections are leak-free.
- If applicable, before making the electrical connection and turning on the tanker pump, good conditions of the electrical socket should be confirmed.

Connecting Hoses and Loading/Unloading Operation

- Use of protective gear: Requisite PPE including safety shoes, a helmet with ear protection, a protective shield or safety goggles, gloves and an air respirator should be worn during handling and connection processes.
- Before connecting the hoses, the gaskets and screw connections should be in good condition.
- Designated tools for connecting hoses should always be utilised.
- Hammering or striking the connections with wrenches should be avoided.
- After the hoses are connected and before opening any valve, hose safety cables should be attached, if applicable.
- To prepare for and carry out the unloading operation, specific instructions of receiving facility should be followed: This includes connecting the hoses, pressurising with gaseous CO_2, etc.
- A screw connection that is under pressure should never be tightened.
- Valves should be handled with care and opened slowly.
- Throughout the entire transfer process, proximity of operation should be close to the tanker's control cabinet, ready to respond to any potential issues that may arise, such as overfilling, leaks, or pump problems.

Purging and Disconnecting Hoses

The purging process is crucial to avoid the creation of dry ice plugs. It is important to adhere to company guidelines, but a general procedure could include:

- After the transfer is complete, the valves should be shut and initially purge only the liquid hose through one valve, preferably the one at the lowest point.
- It is recommended to have a bypass line between the liquid and gas phases to pressurise the liquid line with gaseous CO_2.
- Once purging and depressurisation are finished, hose should be flexible along its entire length (indicating that no dry ice has formed inside the hose) and disconnected using designated tools.
- If applicable, the safety cables should only be removed after the hose has been disconnected.

Checking Discharge / Filling Quantity

- After each unloading / loading, the weight or volume of the ISO tank container should be verified to ascertain the quantity of LCO_2 unloaded / loaded and to ensure it has not been overfilled. Methods to measure fill volume include:
  - Visual or electronic liquid level gauges installed on tanks. They provide a direct measure of the liquid level which can be converted to volume using tank’s dimensions and shape.
  - Pressure gauges to determine pressure of tanks and correlated to volume of liquid inside the tank given known physical properties of LCO_2.

Similarly, during every unloading, the weight or volume of the stationary bulk tanks shall be inspected using trycock valve and/or visual or electronic liquid level gauges installed on tanks to confirm it hasn't been overfilled. If overfilling is detected, any further filling should be stopped and excess volume should be drained and collected until volume is back within safe operating limits.

6.3 Environmental Protection Measures

The potential impact of CO_2 emissions on the environment is significant. CO_2 is a primary greenhouse gas (GHG) contributing to global warming and climate change.

CO_2 emissions resulting from the entire life cycle of LCO_2 offloading systems, including the logistics chain, can have a substantial environmental impact. Therefore, it is crucial to mitigate the release of this gas during offloading operations to fully realise the environmental benefits of CCUS systems.

6.3.1 CO_2 Release Related to Offloading Operations

The majority of unwanted emissions from LCO_2 offloading systems originate during pre-offloading preparation (i.e., introducing CO_2 vapor and cool down) and post-offloading operations (i.e., CO_2 gas freeing).

Performing these processes effectively may unfortunately result in some CO_2 release. For instance, CO_2 leaks could occur when disconnecting dry couplings or through fugitive emissions generated by vibrating or malfunctioning safety valves. Additionally, smaller CO_2 offloading assets may lack the infrastructure to safely collect, store, and dispose of these gas vapour mixtures.

While the general concern about CO_2 emissions is high, the focus is often on larger sources of emissions. However, with growing environmental awareness and regulatory pressure, the importance of managing emissions from smaller sources, like offloading operations, will be getting increasingly recognised.

Being proactive in minimizing CO_2 emissions requires the collaboration and joint initiative of key stakeholders involved to secure the most effective outcome. Potential initiatives that could be adopted, subject to technical and economic viability, include:

- Develop fixed port infrastructure enabling the collection, storage, and disposal of CO_2 vapour and purged gas mixtures.
- Require CO_2 offloading providers as part of the licensing process to pool together resources to facilitate safe collection and disposal of CO_2 emissions.

6.3.2 Guidance on how to Mitigate CO_2 Release During Offloading Operations

Guidelines for mitigating CO_2 release during offloading operations should focus on identifying potential points of CO_2 release at the interface between the offloading system and the LCO_2 receiving vessel/facility, and within the port or terminal end of the offloading process.

It is crucial that the offloading system onboard the ship is arranged so that no gas is discharged to the atmosphere during the offloading of LCO_2. This requirement should be extended to the entire offloading scope, not only the offloading of storage tanks.

The same concern and limitation should be extended to the connection and disconnection procedures.

In view of the importance to minimise the environmental impact of CO_2 offloading operations at ports, the CO_2 vapour should be adequately managed at all stages of offloading operations. All these recommendations should be included in a CO_2 Offloading Management Plan.

6.4 Emergency Response Procedures

6.4.1 Introduction

An effective emergency response plan (ERP) is vital in ensuring that all involved parties are familiarised with the various emergency scenarios and their corresponding responses, which will undoubtedly reduce the time taken to react during an emergency and potentially reduce the number of casualties or damage. This is especially the case (as it can be inferred from the various LCO_2 offloading concepts and from the HAZID workshop discussions) that is expected when the personnel involved may be handling such hazardous material and related offloading operations for their first time.

This section presents the hazard associated with CO_2 as well as some examples of emergency scenarios during LCO_2 offloading operations which references the findings from the HAZID and SIMOPS studies detailed in chapter 7. The hazards associated with CO_2 have been detailed in chapter 1.

In the context of emergency response and from the discussion of the safety studies, the following phenomenon is expected of a LCO_2 release:

As LCO_2 is being transported near a delicate triple point condition (especially for low pressure storage condition) to ensure that CO_2 remains liquefied, it involves sub-zero temperatures depending on the storage/offloading pressure. In the event of any loss of containment, pressurised liquid CO_2 is released to the atmosphere (at ambient pressure) and begins to rapidly expand bringing down the fluid/gas temperature below the release temperature (also known as the Joule-Thomson Expansion effect). This effect may see the formation of dry ice which may pose embrittlement concerns to nearby equipment and structure but would also result in cold burns to personnel in the vicinity, along with the exposure to released sub-zero temperature fluid/gas.

Given that the released CO_2 is cold and coupled with the known density of CO_2 being heavier than air, it is expected that the cold dense CO_2 cloud will have a dispersion profile that tends to sink to the lower elevations and stay low which may pose a toxic and/or asphyxiation concern.

It should be noted that the following sections serve as a general approach to the emergency response during various emergency scenarios occurring during a LCO_2 offloading operation, which should be modified and developed to meet specific project requirements.

6.4.2 Emergency Scenarios and Response

6.4.2.1 Extreme Weather

In the event of an extreme weather (i.e., strong wind and waves, etc.), offloading operations should be suspended with subsequent disconnection of the offloading hoses/arms if deemed necessary. Involved parties should also consider emergency unberthing, especially if the vessels are carrying out a StS offloading at anchorage which is more susceptible to the weather conditions and should inform local port authorities of the intention to do so.

During the pre-offloading meeting, the allowable operating weather envelope should have been discussed and agreed upon with the involved parties, which should also include the emergency actions required to be taken upon deterioration of weather conditions.

6.4.2.2 Loss of Moorings

LCO_2 offloading operations should be suspended immediately in the event of any breakaway of mooring lines. If the loss of mooring is severe enough to result in drifting of the vessel, the offloading hoses/arms should be disconnected to prevent breakaway of offloading hoses/arms and the involved parties should also consider emergency unberthing. Tugs should also be activated for immediate assistance.

6.4.2.3 Blackout

All LCO_2 offloading operations should be suspended during a blackout event as it may result in an unsafe offloading operation with inadequate monitoring of LCO_2 handling within the offloading systems (such as the LCO_2 receiving vessel's cargo tank). There are however, preventive measures in place as required by codes and standards, to provide redundancy in power for the handling system to ensure that the LCO_2 tank's pressure are within safe limits. Resumption of LCO_2 offloading operations can commence once power is restored or if proper mitigation measures that are agreed between all involved parties are in place.

6.4.2.4 Loss of Communication

All LCO_2 offloading operations should be suspended in the event of loss of communication as communication is vital during any offloading operation, given that it involves a close watch between the involved parties to cover all aspects of the offloading operation which is not just limited to the process transfer itself, but also covering the other external factors that may influence the success of an offloading operation.

6.4.2.5 Ship Collision/Allision

The emergency situation evaluation for collision/allision events should consider potential LCO_2 containment breaches and LCO_2 spills. The immediate actions taken and follow-up responses should be documented in an emergency response plan. The involved parties of the LCO_2 offloading operations should activate their own existing emergency response plan and close communication between the involved parties should be maintained.

6.4.2.6 Over-pressurisation

Over-pressurisation of the offloading manifold lines and the receiving LCO_2 tanks can occur due to a number of causes as identified during the HAZID. In the event if any overpressure is detected, offloading operations should be suspended immediately, if not already programmed to do so (actions such as pump trips, closure of tank inlet valves, etc.) upon reaching a certain pressure transmitter setpoint. Measures shall be put in place to prevent thermal expansion of trapped liquids which may lead to further overpressure.

It should be noted that vapour return capabilities are assumed to be provided which deals with the excessive BOG generated during offloading operations. If it is still deemed insufficient, cargo tanks are fitted with PSVs as a last resort to vent out excess pressure to revert the cargo tank into a safe state. Water deluge system should be activated to cool down the LCO_2 tank and equipment if the source of over-pressurisation is due to an external fire in the vicinity.

6.4.2.7 Uncontrolled Venting

In the event of an uncontrolled venting due to over-pressurisation event as described above, or spurious activation of PSVs, offloading operations should be suspended immediately. Measures shall be put in place to prevent thermal expansion of trapped liquids which may lead to further overpressure.

There are various noticeable visual cues such as icing on the vent mast or a white plume exiting the top of the vent mast which will occur during a venting scenario, and it can be quickly identified as an uncontrolled venting scenario if there isn't a planned venting operation.

Given that the density of CO_2 is higher than air, coupled with the low temperature upon release, the CO_2 plume is likely to sink to lower elevations or stay low to the ground as it disperses from the release source. Therefore, crew onboard the vessel should be made aware of the expected dispersion direction so that they will remain upwind of the dispersed CO_2 plume. Additional precautions (which could include shutting of ventilation inlets upon confirmed CO_2 detection) need to be provided for ventilated occupied spaces such as machinery spaces, accommodation, etc., to prevent CO_2 from drifting into such spaces.

Adequate and appropriate personal protective equipment should be provided at strategic locations across the facility to allow for personnel to escape safely to defined 'safe areas'.

Emergency communication channels should also be established to inform the involved parties (vessel crew and onshore personnel within the receiving facility), as well as the port authorities of a loss of containment event, to allow for information to be quickly disseminated to other vessels and surrounding facilities in the vicinity. The emergency communication shall also be extended to emergency services as there may be a need to seek additional 3rd party support.

6.4.2.8 Loss of Pressure

As highlighted in the characteristics of CO_2 and identified during the HAZID workshop, the storage and transfer conditions are crucial in ensuring that LCO_2 is stored and transferred as liquefied gas and CO_2 vapor is transferred as gas. During LCO_2 offloading operations, it is essential that the storage tank offloading LCO_2 receives the return vapour from the receiving cargo tank to maintain the storage tank pressure, so as to ensure that the contents within remain in a liquefied form. In the event if the process pressure does drop below the triple point pressure, the contents within the storage tank and associated transfer system may solidify, resulting in blockages and subsequent over-pressurisation of the upstream systems such as the receiving LCO_2 tank vapour return header.

Provisions for pressure build-up unit may be useful, but only for the storage tanks as they will not be able to reach the segments of the associated transfer system. Consideration should be given for provisions of heating elements / devices / arrangements (portable or fixed) to remove the icing within the affected segments.

6.4.2.9 LCO_2/CO_2 Loss of Containment (Toxic Impact)

In the event of LCO_2 or CO_2 release or detection (refer to the HAZID section for the possible scenarios which includes the storage tank, offloading manifold and offloading hoses/arms), all LCO_2 offloading operations should be immediately suspended and the offloading ESD system should be activated with measures that shall be put in place to prevent thermal expansion of trapped liquids which may lead to further overpressure. The offloading system should be depressurized, disconnected to commence unberthing, provided it is safe to do so.

Given that the density of CO_2 is higher than air, coupled with the low temperature upon release, the CO_2 plume is likely to sink to lower elevations or stay low to the ground as it disperses from the release source. Therefore, crew onboard the vessel should be made aware of the expected dispersion direction so that they will remain upwind of the dispersed CO_2 plume. Additional precautions (which could include shutting of ventilation inlets upon confirmed CO_2 detection) need to be provided for ventilated occupied spaces such as machinery spaces, accommodation, etc., to prevent CO_2 from drifting into such spaces.

Adequate and appropriate personal protective equipment should be provided at strategic locations across the facility to allow for personnel to escape safely to defined 'safe areas'.

Emergency communication channels should also be established to inform the involved parties (vessel crew and onshore personnel within the receiving facility), as well as the port authorities of a loss of containment event, to allow for information to be quickly disseminated to other vessels and surrounding facilities in the vicinity. The emergency communication shall also be extended to emergency services as there may be a need to seek additional 3rd party support.

There needs to be a distinction between the extent of severity of a loss of containment event which shall trigger a tiered response, and this, together with the evacuation plans as part of the ERP, has to be developed for individual facilities on a case-by-case basis.

6.4.2.10 LCO_2 Loss of Containment (Low Temperature Impact)

In the event of LCO_2 or CO_2 release or detection (refer to the HAZID report for the possible scenarios which includes the storage tank, offloading manifold and offloading hoses/arms), all LCO_2 offloading operations should be immediately suspended and the offloading ESD system should be activated with measures that shall be put in place to prevent thermal expansion of trapped liquids which may lead to further overpressure. The offloading system should be depressurized, disconnected to commence unberthing, provided it is safe to do so.

A loss of containment of pressurized LCO_2 to ambient conditions may result in the formation of dry ice which poses an embrittlement concern to nearby equipment and structure, as well as potential cold burns to personnel in the vicinity, along with the exposure to released sub-zero temperature fluid/gas.

Adequate and appropriate personal protective equipment should be provided at strategic locations across the facility to allow for personnel to escape safely to defined 'safe areas'. Generous amount of water should also be provided to protect the ship's superstructure to prevent any form of embrittlement damage, if deemed practicable.

6.4.2.11 Injury to Personnel

The immediate hazards of exposure to LCO_2 are related to toxic exposure, cold burns and asphyxiation. Apart from existing contingencies or emergency response plans to deal with injuries, dedicated emergency response should be considered, depending on the type and extent of LCO_2 exposure on the affected personnel.

6.4.3 Main Elements of ERP

Regardless of the type of emergencies that may occur during the LCO_2 offloading operation, the ERP should include elements of the following:

1. Raising an emergency alert - This should be done through visual and audio means to alert everyone within the affected vicinity of an emergency. Consideration can also be given to differentiate the

alerts for different categories of emergencies. More importantly, involved parties of the LCO_2 offloading operation should also agree on a common alert so as to avoid confusion from different alerts coming from two different facilities (i.e., offloading vessel and receiving vessel or receiving vessel and terminal, etc.)

2. Activating emergency shutdown protocol - This usually involves the suspension of all offloading activities and activation of ESD systems with the aim of isolating the offloading system to minimize the amount of hazardous material that is released due to events leading to loss of containment. There should also be a Ship-to-Ship/Shore link (SSL) in place which will immediately trip the offloading vessel's pump without the need for operator intervention, which needs to be checked during the vessel compatibility study.

3. Establishing emergency communications - Once the involved parties are aware and are taking the necessary steps to address the ongoing emergency, port authorities and emergency services should be immediately informed of the ongoing emergency, so as to allow for swift dissemination of critical information for the surrounding facilities to be able to react accordingly.

4. Establishing evacuation plan, emergency escape routes and muster points - Dedicated escape routes should be established to allow personnel to escape safely and swiftly to a dedicated muster point within the facility. Wind directions should also be taken into consideration given that the concern of a loss of containment event is partly due to toxic dispersion of CO_2. This information should be placed at strategic locations across the facility where personnel are expected to be present.

5. Description of core procedures and incident specific procedures - The ERP will describe the Core procedures which are typically implemented across a broad variety of incidents and act as "building blocks" for incident specific response procedures. The incident specific procedures and mitigation actions for emergency scenarios such as enumerated in Section 2 above are also described in the ERP.

6. Location of PPE and emergency response equipment - Appropriate PPE is required and should be placed at strategic locations across the facility which is easily accessible to personnel in the event of the need to escape or enter in a location where an incident has taken place. Other emergency response equipment including firefighting equipment for fire in adjacent area which may affect the storage or offloading of LCO_2, water spray arrangements, safety equipment, rescue equipment such as stretchers etc., First aid equipment etc. should also be available at suitable locations. The location of the equipment should be identified in the ERP, ideally in a general arrangement drawing / plan.

7. Duties and responsibilities of personnel - The emergency response team should be identified in the ERP and the duties and responsibilities described for each individual team member. Substitutes should be nominated for each role in case of injury of the primary emergency team member.

8. Emergency drills - Emergency drills covering the abovementioned emergency scenarios (which can include consideration for a joint exercise) shall be held routinely to allow all involved personnel to be familiarized with the emergency scenarios and associated responses. This will also help to test the robustness of the developed ERP to identify any other areas of improvement.

It shall be noted that the formulation of an ERP should not be limited to the points covered above, but rather, tailored to individual facilities requirements. The ERP should also meet the International Safety Management Code (ISM) code requirements for the ship and local regulatory requirements for receiving vessel related facilities and onshore related facilities.

6.4.4 Examples of Typical Emergency Responses

The following tables provide details of a generic emergency response envisioned during various emergency scenarios which focuses on scenarios that are unique to LCO_2 offloading operations. This excludes typical marine related emergencies such as ship collision, blackout, loss of mooring, as they are assumed to be well covered by existing vessel's emergency response in the industry today.

6.4.4.1 Emergency Scenario – Uncontrolled Venting from LCO_2 Offloading Ship (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.	√	√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.2 Emergency Scenario – Uncontrolled Venting from LCO_2 Receiving Vessel (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.	√	√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.3 Emergency Scenario – Uncontrolled Venting from LCO_2 Receiving Vessel (during Ship-to-Shore offloading at terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.		√		
Initiate activation of Ship-to-Shore link between the offloading vessel and terminal offloading facilities		√	√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)		√	√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to surrounding facilities				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.4 Emergency Scenario – LCO_2/CO_2 Loss of Containment (Toxic Impact) on the Offloading Ship (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.	√	√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder’s procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.5 Emergency Scenario – LCO_2/CO_2 Loss of Containment (Toxic Impact) on the LCO_2 Receiving Vessel (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.	√	√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.6 Emergency Scenario – LCO_2/CO_2 Loss of Containment (Toxic Impact) on the LCO_2 Receiving Vessel (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.		√		
Initiate activation of Ship-to-Shore link between the offloading vessel and terminal		√	√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)		√	√	
Initiate Terminal emergency response plan		√	√	
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to surrounding facilities				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.7 Emergency Scenario – LCO_2/CO_2 Loss of Containment (Toxic Impact) at the Bulk Liquid Storage Terminal (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert			√	
Initiate suspension of all offloading activities			√	
Initiate activation of ESD systems			√	
Initiate emergency response for the vessel which includes informing crew of expected toxic gas dispersion direction to allow for safe evacuation.	√			
Initiate activation of Ship-to-Shore link between the offloading vessel and terminal	√		√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√		√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services			√	√
Relay key information to surrounding facilities				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.8 Emergency Scenario – LCO_2/CO_2 Loss of Containment (Low Temperature Impact) on the Offloading Ship (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the affected vessel which may include providing generous amount of water to protect the ship's superstructure from embrittlement (if deemed practicable)	√			
Initiate emergency response for the vessel in tandem		√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.9 Emergency Scenario – LCO_2 Loss of Containment (Low Temperature Impact) on the LCO_2 Receiving Vessel (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the affected vessel which may include providing generous amount of water to protect the ship's superstructure from embrittlement (if deemed practicable)		√		
Initiate emergency response for the vessel in tandem	√			
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.10 Emergency Scenario – LCO_2 Loss of Containment (Low Temperature Impact) on the Offloading Ship (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the affected vessel which may include providing generous amount of water to protect the ship's superstructure from embrittlement (if deemed practicable)	√			
Initiate activation of Ship-to-Ship link between the offloading vessel and receiving vessel	√		√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√		√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.11 Emergency Scenario – LCO_2 Loss of Containment (Low Temperature Impact) at the Bulk Liquid Storage Terminal (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert			√	
Initiate suspension of all offloading activities			√	
Initiate activation of ESD systems			√	
Initiate emergency response for the vessel in tandem	√			
Initiate activation of SSL between the offloading vessel and terminal	√		√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√		√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services			√	√
Relay key information to surrounding facilities				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.12 Emergency Scenario – Loss of Pressure on LCO_2 Offloading Ship (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the vessel which includes activating heating elements / devices / arrangements (portable or fixed) to remove icing within the affected segments	√			
Initiate emergency response for the vessel in tandem		√		
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.13 Emergency Scenario – Loss of Pressure on LCO_2 Receiving Vessel (During StS Offloading at Anchorage)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert		√		
Initiate suspension of all offloading activities		√		
Initiate activation of ESD systems		√		
Initiate emergency response for the vessel which includes activating heating elements / devices / arrangements (portable or fixed) to remove icing within the affected segments		√		
Initiate emergency response for the vessel in tandem	√			
Initiate activation of SSL between the offloading vessel and receiving vessel	√	√		
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√	√		
Establish emergency communications with port authorities and emergency services		√		√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.14 Emergency Scenario – Loss of Pressure on LCO_2 Offloading Ship (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert	√			
Initiate suspension of all offloading activities	√			
Initiate activation of ESD systems	√			
Initiate emergency response for the vessel which includes activating heating elements / devices / arrangements (portable or fixed) to remove icing within the affected segments	√			
Initiate activation of Ship-to-Ship link between the offloading vessel and receiving vessel	√		√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√		√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services	√			√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.4.4.15 Emergency Scenario – Loss of Pressure at Bulk Liquid Storage Terminal (During Ship-To-Shore Offloading at Terminal)

Emergency Responses	LCO_2 offloading ship	LCO_2 receiving vessel	Bulk liquid storage terminal	Port authority & emergency services
Initiate an emergency alert			√	
Initiate suspension of all offloading activities			√	
Initiate activation of ESD systems			√	
Initiate emergency response for the vessel in tandem	√			
Initiate activation of Ship-to-Ship link between the offloading vessel and receiving vessel	√		√	
Prepare for loading hose/arm disconnection and unmooring, including emergency unberthing (if necessary)	√		√	
Initiate Terminal emergency response plan			√	
Establish emergency communications with port authorities and emergency services			√	√
Relay key information to nearby vessels at anchorage				√
Initiate emergency responder's procedure to provide additional support (i.e., medical evacuation)				√

6.5 References

[1] International Organization for Standardization., "IEC 31010:2019 Risk management — Risk assessment techniques," International Organization for Standardization, 2019.

[2] DNV, "DNV-RP-F104 Design and operation of carbon dioxide pipelines," DNV, 2021.

[3] International Organization for Standardization, "ISO 27913:2016 Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems," International Organization for Standardization., 2016.

[4] International Organization for Standardization, "ISO 17776:2016 Petroleum and natural gas industries — Offshore production installations — Major accident hazard management during the design of new installations," International Organization for Standardization, 2016.

[5] International Organization for Standardization, "ISO 19901-7:2013 Petroleum and natural gas industries Specific requirements for offshore structures Part 7: Stationkeeping systems for floating offshore structures and mobile offshore units, 2013.

[6] International Organization for Standardization, "ISO 16904:2016 Petroleum and natural gas industries — Design and testing of LNG marine transfer arms for conventional onshore terminals," International Organization for Standardization, 2016.

[7] OCIMF, Mooring Load Analysis during Ship to Ship Transfer Operations, OCIMF, 2022.

7. Safety Studies

7.1 HAZard IDentification (HAZID)

7.1.1 Overview

A Hazard Identification (HAZID) workshop was conducted as part of the "Concept Study to Offload Onboard Captured Carbon Dioxide". The workshop was held remotely from 12th – 15th September 2023 via videoconference means involving members of GCMD, LR/Arup and a number of industry study partners from diverse backgrounds who provided a wealth of experience and expertise during the HAZID discussions.

The aim of the HAZID study was to identify and risk assess the hazards associated with the LCO_2 offloading concepts that were shortlisted previously (See Chapter 3). Given that this is a conceptual study, the HAZID also aimed to identify potential engineering/maritime/logistic factors to be considered for the next phases of the project. However, as the discussion progressed for the various nodes during the HAZID, it was clear that the various LCO_2 offloading concepts are very conceptual in nature with a number of assumptions required to be made such as the design considerations, end-user demand/requirements, location of application, etc. As these assumptions will undoubtedly have an impact on the risk ranking, it was further discussed and agreed with the HAZID team during the workshop that risk ranking will not be carried out for this HAZID. Risk ranking can be performed with this study as basis when details of vessels and specifications on concept design are available.

A total of 131 scenarios were identified, with a number of concerns that are related mainly to the safety, operational and feasibility aspects of the four LCO_2 offloading concepts. The list of the concerns and applicability to each of the LCO_2 offloading concepts is summarised in the table below.

Table 7.1 – List of concerns and applicability to each LCO_2 offloading concept (HAZID)

List of Concerns	Applicability to LCO_2 offloading concepts (Y/N)			
	Concept 1	Concept 2	Concept 3	Concept 4
Various causes resulting in loss of containment of LCO_2 and subsequent cold dense CO_2 cloud dispersion or the development of cold temperature zones	Y	Y	Y	Y
Incompatibilities between merchant vessels and LCO_2 receiving vessels / receiving terminals	Y	Y	Y	N
Impurities in LCO_2 which affects the storage conditions and even possibly, the material selection for the LCO_2 offloading system.	Y	Y	Y	Y
Unfamiliarity with LCO_2 offloading processes, especially when LP/MP or MP/LP interface is involved	Y	Y	Y	Y
Training and competency of the vessel's crew with regards to LCO_2 offloading operations	Y	N Note 1	Y	N Note 1
Undefined drying and purging requirements pre/post LCO_2 offloading operations	Y	Y	Y	Y

List of Concerns	Applicability to LCO_2 offloading concepts (Y/N)			
	Concept 1	Concept 2	Concept 3	Concept 4
Logistics reality at a container terminal where it is expected to receive containerships having OCCS, sailing with different types of fuels with varying level of impurities, coupled with dedicated space requirement for storage of empty ISO tank containers	N	N	N	Y
Expected voyage duration of a containership in comparison to the BOG holding time of the ISO tank containers as it is expected to have 10-15 LCO_2 tank containers to be fully filled before carrying out the next tank swapping.	N	N	N	Y

Note 1: Concept 2 involves LCO_2 receiving vessels and Floating CO_2 Storage Units (FCSUs) that are considered gas carriers with crew already expected to be IGC trained. As for concept 4, it deals with LCO_2 ISO tank container which is treated as a normal container transfer operation.

While there is less complexity from a process perspective for concept 4 - ship-to-terminal with ISO tank containers, additional consideration needs to be given to address the logistics reality of a container terminal. The feasibility of concept 4 very much depends on the amount of empty LCO_2 ISO tank containers available for containerships adopting OCCS to carry out the tank swapping which still has to take into account the concern of impurities within LCO_2. The expected voyage duration and BOG holding time of the first fully filled LCO_2 ISO tank container needs to be studied further as that may require the container ship to offload the full LCO_2 ISO tank container earlier than anticipated. The holding time may range from 30 to 90 days, depending on the environmental conditions and the initial filling conditions. Typically, ships may fill up all LCO_2 ISO tank containers onboard and swap them at one terminal in one go. However, with an expectation of having 10-15 LCO_2 tanks fully filled before next tank swapping, there is a risk that the tanks initially filled may exceed the BOG holding time if they arrive at a terminal where offloading is possible after 30 days or more.

Throughout the HAZID discussions, it became evident that there is work yet to be completed to facilitate LCO_2 offloading concepts. One of the primary concerns emphasized across all offloading concepts was the impurities of LCO_2. This not only poses a safety risk due to material incompatibilities within the supply chain, but the type and concentration of impurities may also impede the progress of OCCS adoption. This is particularly significant as different end-users may have varied LCO_2 impurity specifications.

In total, there were 54 recommendations provided by the study to address the abovementioned concerns, which should be taken forward into the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

7.1.2 Aim

The aim of the HAZID study was to identify and risk assess the hazards associated with the shortlisted LCO_2 offloading concepts. As this was a conceptual study, the HAZID also aimed to identify potential engineering/maritime/logistic factors to be considered for the next phases of the project.

7.1.3 Scope of Work

The scope of work for the HAZID is limited to the hazards and risks (Safety) arising from the shortlisted LCO_2 offloading concepts. It is assumed that the risks associated with the onboard carbon capture and subsequent liquefaction of CO_2 onboard the vessel have already been addressed in other risk assessments and will not be further discussed. The battery limits for this Project would be from the LCO_2 offloading tank onboard the vessel to the LCO_2 storage tank/facility onshore.

The general design envelopes for offloading scenarios are shown in Table 2.27.

The shortlisted concepts are:

- Concept 1 – Ship-to-liquid bulk terminal, as described in section 3.3.2.
- Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel, as described in section 3.3.3.
- Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel, as described in Section 3.3.4.
- Concept 4 – Ship-to-terminal with ISO tank containers, as described in Section 3.3.5.

Note: It was further discussed and agreed with the HAZID team during the workshop that risk ranking will not be carried out for this HAZID as this project is still in a conceptual stage with a number of assumptions being made around the design, end-user demand/requirements, location of application, etc., which may have an impact on the risk ranking.

7.1.4 Typical Steps of an Offloading Cycle

The steps typically associated with an offloading cycle (with reference to concept 3) [Note 1] are listed below:

- Pre-operations – This refers to the preparation phase prior to mobilisation of any vessel for the various offloading concepts, which usually involves a compatibility assessment [Note 2] for the different type of offloading vessels (i.e., merchant ship to LCO_2 receiving vessel, merchant ship to bulk liquid terminal, etc.)
- Transit & mooring/unmooring at anchorages for offloading – This refers to the merchant ship transiting to a designated anchorage to offload LCO_2 to LCO_2 receiving vessel.
- Offloading of LCO_2 – This refers to the actual offloading operation, which also includes the pre/post transfer checks prior to commencement of offloading and transiting.
- Transit, berthing & mooring/unmooring at bulk liquid terminal – This refers to the actual activity itself where the LCO_2 receiving vessel is transiting to the bulk liquid terminal. It will be a repeat of the above steps on mooring/unmooring, pre/post transfer and the actual LCO_2 offloading operations.

Note 1: Concept 3 covers StS and ship-to-shore offloading activities which represents concept 1 and concept 2. As for concept 4, it is for a containership where LCO_2 ISO tank containers are transported to designated container terminals and loaded onto trucks, with no offloading intended to be carried out at the container terminals.

Note 2: An offloading compatibility assessment basically looks into many aspects of offloading (i.e., physical compatibilities such as location of offloading/receiving stations, difference in vessel's freeboard, mooring load and arrangements, length and type of hoses/arms, crane outreach and process compatibilities such as BOG management, process conditions of the offloading/receiving vessel, ESD-Ship-to-Ship/Shore Link, offloading rate, purging requirements) and it is through this assessment (if done for the first time for a particular combination of vessels) where issues might be highlighted. Offloading compatibility assessment needs to be done between the different types of merchant ships and receiving vessels.

One foreseeable challenge would be the type of merchant ships that are offloading LCO_2. Different ships may have space constraints which would affect where their offloading stations are located, and this may pose an issue considering that the cargo manifold on LCO_2 receiving vessels (gas carriers) are normally located midship. However, this can only be picked up during the bunkering compatibility assessment between the merchant ship and receiving vessel.

7.1.5 HAZID Study

7.1.5.1 HAZID Objectives

The objectives of the HAZID Study were to:

- identify hazards associated with the LCO_2 offloading concepts, in particular how they can be realised (what can go wrong, and how?). This shall focus on risks to personnel.
- determine reasonably foreseeable consequences of these hazards
- review system safeguards / control measures to ensure suitability and understand what measures could be taken to eliminate, reduce / minimise the consequences and frequency of such hazards
- record actions / recommendations for further consideration in the next phase of design

7.1.5.2 HAZID Methodology

A HAZID study is a methodical 'creative brainstorming' technique used to identify hazards and operational issues associated with a design or process.

A guideword-based technique to identify hazards shall be used based upon LR experience with guidance from the following sources:

BS ISO 31000: 2018, Risk Management – Principles and Guidelines [1]

BS ISO 31010: 2019, Risk Management – Risk Assessment Techniques [2]

The workshop was facilitated and scribed by a LR Risk Specialist.

HAZID guidewords described in Section 7.1.5.6 were applied, initiating and encouraging discussions on possible events that may lead to unplanned outcomes. These prompts are based upon previous experience and indicate the types of hazards that are thought to be applicable to the various offloading concepts.

Identification of hazards and causes

Possible hazards were identified by applying the guidewords. If a credible potential hazardous event is identified the HAZID team considered possible causes that may lead to this. If no meaningful hazards or causes were identified this was recorded in the minutes.

Evaluation of consequences

The consequences of each cause analysed by the HAZID team was assessed to see if the unplanned incident could lead to harm to persons, the consequences of which were discussed and recorded.

Evaluation of safeguards

The HAZID team considered the safeguards that are present (or proposed) to see if they provide sufficient protection. With these safeguards in place, the level of risk was qualitatively assessed to the criteria outlined in Section 3.9 [Note 1]. If the judgement of the HAZID team was that there are insufficient safeguards (usually for Medium and High risks), additional mitigation measures were recommended.

Recommendations

The final stage of the study was to review the list of recommendations that were raised to ensure that they are clear and have responsible persons assigned to them [Note 2].

Note 1: It was discussed and agreed with the HAZID team the workshop that risk ranking will not be carried out for this HAZID as this project is still in a conceptual stage with a number of assumptions being made around the design, end-user demand/requirements, location of application, etc., which may have an impact on the risk ranking.

Note 2: In the case for this project which is in a conceptual phase, these recommendations are actions that should be taken forward in the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

7.1.5.3 Assumptions

The HAZID study assumed the following:

- Concept 3 was selected as the representative scenario as it is the most complex out of the four concepts, involving StS LCO_2 offloading at anchorage and subsequently ship-to-shore LCO_2 offloading at terminal. Bulk of the discussion for concept 3 is expected to be applicable for the other concepts, given the similarities in the transfer approach, or the LCO_2 offloading processes. As such, concept 1 and 2 were done by-difference to concept 3.
- For the various concepts, both LP and MP operating pressures were discussed (where applicable) as they each present their own set of risk.
- Only single failures were considered, i.e., multiple failures were not considered credible, unless they can go undetected (hidden failures).
- The systems, equipment and layout is per the information shared prior to the HAZID workshop.
- The proposed / intended safeguards shall be installed and function as outlined.
- SIMOPs related issues were not discussed in this HAZID as there is a separate session for SIMOPs discussion.

7.1.5.4 Team Members

The HAZID team comprised the following:

Table 7.2 – HAZID team

Name	Role	Organisation	Title	12 Sep 23	13 Sep 23	14 Sep 23	15 Sep 23
Nelson Loo	Facilitator	LR MPS	Risk Specialist	Y	Y	Y	Y
Sun-Joo Choi	SME	LR MPS	Senior Risk Specialist	Y	Y	N	N
Brijesh Tewari	SME	LR MPS	Lead Maritime Decarbonisation Consultant	Y	N	Y	Y
Naroshinii A Annaselam	SME	LR MPS	Sustainability Specialist	Y	Y	Y	N
Jose Navarro	SME	LR	LR Global Gas Technology Director	Y	Y	Y	N
Etemad Hamid	SME	LR	Global Gas Technology Specialist	Y	Y	Y	Y
Cossel Chang	SME	ARUP	Associate Maritime Engineer	N	N	N	N
Lydia Green	SME	ARUP	Ports & Maritime Engineer	Y	N	N	N
Sinthujan Pushpakaran	SME	ARUP	Energy Engineer	Y	Y	Y	Y
Ben Rigby	SME	ARUP	Senior Process Engineer	Y	Y	Y	N
Mark Button	SME	ARUP	Associate Engineer	N	N	N	N
Victor Pang	SME	GCMD	Senior Associate	Y	Y	Y	Y
Rashim Berry	SME	EPS	Senior Advisor, Special Projects	Y	N	N	N
Capt. Suraj	SME	EPS	General Manager, Operations	Y	N	N	N
Capt. Anish Saxena	SME	EPS	Assistant Operations Manager	Y	Y	N	N
Nishudhan Ravi	SME	EPS	Assistant Operations Manager	Y	N	N	N

Name	Role	Organisation	Title	12 Sep 23	13 Sep 23	14 Sep 23	15 Sep 23
Ker Hong Yeow	SME	MISC	Decarbonisation, New Energy & Decarbonisation	Y	Y	Y	N
Kim Sang Su	SME	MISC	Project manager - Floating CO_2 Storage Unit (FCSU) concept engineering	Y	Y	N	N
Muhammad Na	SME	MISC	Manager	N	N	N	N
Kenneth George Ng	SME	MISC	Head, Zero Emissions Vessel Project	Y	Y	Y	Y
John Baptist	SME	MISC	Head of Decarbonisation	Y	Y	Y	Y
Prabagaran Balasundaram	SME	AET-Tankers	Chartering Manager	Y	Y	Y	Y
Meninderjit	SME	Eaglestar	Manager, Zero Emissions	N	N	N	N
Françoise van den Brink	SME	Port of Rotterdam	Sr. Advisor Energy Transition	N	N	Y	N
Royen Gultom	SME	Seatrium	Assistant Process Manager	Y	Y	Y	Y
Jei Rollicer Bagonoc	SME	Seatrium	Process Engineer	Y	Y	Y	Y
Thomas Sim	SME	Jurong Port	Lead Engineer, Energy Terminals - Energy Transition	Y	Y	Y	Y
Puneet Verma	SME	Chevron	Senior LNG Ship Shore Interface Advisor-Marine Terminals	Y	Y	N	Y
Gary Pang	SME	GASPL	Executive Director	Y	N	Y	N
Amar Chandiram	SME	Shell	Manager	Y	N	Y	N
Manish Singal	SME	Shell	Shipping and Maritime Technology Manager	Y	N	N	N

Name	Role	Organisation	Title	12 Sep 23	13 Sep 23	14 Sep 23	15 Sep 23
Ryo Miyoshi	SME	K-Line	Manager, GHG Reduction Strategy Team	Y	N	Y	N
Kenichi Ohki	SME	K-Line	Manager	Y	N	N	N

7.1.5.5 HAZID Nodes

The HAZID covered the following nodes:

Table 7.3 – HAZID nodes

Nodes	Description
Concept 3, Two-stage ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel	
1	Transit, berthing & mooring of ship-to-LCO_2 receiving vessel
2	LCO_2 transfer to LCO_2 receiving vessel (StS)
3	Transit, berthing & mooring of LCO_2 receiving vessel at bulk liquid terminal
4	LCO_2 offloading to bulk liquid terminal (ship-to-shore)
5	Unmooring and departure of LCO_2 receiving vessel
Concept 1, Ship-to-liquid bulk terminal	
6	Node assessed by-difference to concept 3
Concept 2, Ship-to-floating CO_2 Storage with intermediate LCO_2 receiving vessel	
7	Node assessed by-difference to Concept 3
Concept 4, Ship-to-terminal with ISO tank containers	
8	Unloading of LCO_2 ISO tank containers from ship-to-shore
9	Transfer from LCO_2 ISO tank containers to storage at bulk liquid terminal

7.1.5.6 HAZID Prompts / Guidewords

The following prompts/guidewords listed below were suggested to represent the project to suit and match the nature of the LCO_2 offloading concepts. It should be noted that the guidewords have been applied to discuss the hazards arising from the introduction of the LCO_2 offloading concepts (either impact from/towards the LCO_2 offloading concepts).

- External hazards
    - Natural and environmental hazards (e.g. climatic extremes, lightning, seismic events, erosion and subsidence)
    - Effect of facility on surroundings (e.g. proximity to adjacent installation, proximity to transport and proximity to population)
    - Effect of man-made hazards (e.g. security hazards, social/political unrest and ship collision)
    - Infrastructure (e.g. communication, supply support, mutual aid and emergency services)
    - Environmental damage (e.g. discharges to air/water (venting), emergency discharges and water disposal)
- Facility hazards

  - Process hazards (e.g. loss of containment of toxic inventory, overfilling, over-pressurisation, ruptures, impurities and embrittlement)
  - Utility hazards (e.g. fire water system, heating/cooling mediums, power supply, drains/sumps (spill collection), inert gas, air and nitrogen)
  - Maintenance hazards (e.g. maintenance philosophy and provisions for safe maintenance)
  - Construction/existing facilities
  - Other hazards (e.g. crane operations and stability/buoyancy)
- Health hazards
  - Toxic effects
  - Cold burns

7.1.5.7 Characteristics of CO_2

The characteristics of CO_2 have been detailed in Section 1.2.

7.1.5.8 Hazards Associated with CO_2

The hazards associated with CO_2 have been detailed in Section 1.4.

7.1.5.9 Documents Reviewed

The HAZID workshop was based on the following documents that were provided pre-HAZID.

Table 7.4 – Documents reviewed

Document No.	Description	Rev
2301-66993 – Part A	Concept Study to Offload Onboard Captured Carbon Dioxide (Part A: Onboard Storage of Captured Carbon Dioxide)	0
2301-66993 – Part B1	Concept Study to Offload Onboard Captured Carbon Dioxide (Part B1: Offloading Concepts)	0

7.1.5.10 Risk Acceptance Criteria

Initially, risk ranking was proposed to be carried out for the HAZID. However, as the discussion progressed for the various nodes during the HAZID, it was clear that the various LCO_2 offloading concepts are very conceptual in nature with a number of assumptions required to be made such as the design considerations, end-user demand/requirements, location of application, etc. As these assumptions will undoubtedly have an impact on the risk ranking, it was further discussed and agreed with the HAZID team during the workshop that risk ranking will not be carried out for this HAZID.

7.1.6 HAZID Results

7.1.6.1 Results Discussion

There were a total of four LCO_2 offloading concepts assessed during the HAZID, with concept 3 being selected as the representative concept (with concept 1 and 2 being assessed by-difference) as it covers both the ship-to-ship and ship-to-shore aspects of LCO_2 offloading, while concept 4 was discussed as an independent node as it involves container loading and truck offloading which is a different type of offloading operation.

Throughout the discussion of the offloading concepts, a total of 131 scenarios were identified, with a number of concerns that are related mainly to the safety, operational and feasibility aspects of the LCO_2 offloading concept, which will be covered in the sections below.

<u>Safety Aspects</u>

For the safety aspects, the concern is associated with the possibility of loss of containment of LCO_2 during LCO_2 offloading operations which can be caused by some of the following examples:

- Extreme weather (i.e., temperature or wind / waves) resulting in excessive BOG generation or breakaway of LCO_2 transfer hoses /arms
- LP/MP interface not adequately handled between the offloading vessel and LCO_2 receiving vessel / receiving terminals (i.e., bulk liquid terminals or bulk storage facilities)
- Impurities in LCO_2
- Operator error during line-up resulting in over-pressurisation or overfilling or loss of containment
- Mechanical failure of LCO_2 offloading system (i.e., pipes, valves, flanges, etc.)
- Dropped objects / swinging loads
- Ship collision / allision / grounding
- LCO_2 tank PSV venting

For most of the causes identified, there were preventive and mitigative safeguards in place which consists of pressure and level monitoring (with alarm and executive action), pressure safety devices, spill containment, ESD system and procedural controls related to offloading activities in general. However, given that OCCS adoption and associated vessel design for merchant ships (while merchant ship in concept 3 refers to a bulk carrier, it can actually be a tanker, as seen in concept 1, or even possibly a containership) are still in the early stages, there may be potential incompatibility issues between the merchant ships and LCO_2 receiving vessels or receiving terminals which will affect how the LCO_2 offloading operations will be carried out. Furthermore, there is also uncertainty regarding the amount of impurities present within each merchant ship's captured LCO_2 which poses an additional concern to the receiving vessel / receiving terminal as there may be a potential impact to the design of the LCO_2 offloading / receiving system. Also, given that there are no actual LCO_2 offloading operations that have taken place before, most procedures are related to offloading operations in general and are not made specific for LCO_2, which is a concern, especially when there is LP/MP or MP/LP interface between the offloading vessel and receiving vessel that requires additional equipment to be operated or certain parameters (such as returning pressure from LP storage to MP storage) to be closely monitored, to ensure that there is no process upset during the offloading. As such, several recommendations were raised to address these issues:

- Standards need to be developed for OCCS to standardize the amount of impurities present in the captured CO_2 or liquefied CO_2 prior to transfer to LCO_2 receiving vessel or storage.
- Ensuring that a compatibility assessment is carried out between the merchant ship and LCO_2 receiving vessel / receiving facility.
- Ensuring that a detailed transfer process between LP and MP systems is developed for both ship-to-ship and ship-to-shore operations.

In the event of a loss of containment of LCO_2, the main safety concern was the cold dense CO_2 cloud dispersion (density of CO_2 is 1.87kg/m^3 as compared to density of air which is 1.29kg/m^3) which will tend to stay low or sink to lower elevations, rather than dispersing upwards into atmosphere, and this poses a toxic and asphyxiation risk to personnel working on deck or at lower elevations. Nearby vessels that are of a lower draft (i.e., water barges) than the merchant ship were also found to be susceptible to any loss of containment of LCO_2 on the merchant vessel for the same reasons explained above.

Several recommendations were raised regarding this concern which include:

- Consideration for Ship-to-Shore/Ship ESD link provisions to minimise the amount of inventory of LCO_2 that can be released, thus limiting the extent of CO_2 dispersion.
- Ensuring that vibrational related impact from proposed location of LCO_2 offloading systems (for marine vessels has been taken into consideration during design.
- Consideration for optimisation of the location of the vent mast to minimize toxic effect of CO_2 dispersion to personnel.
- Consideration for implementation of spill containment systems for the LCO_2 offloading system (some examples include flange/splash guards to minimise propagation of LCO_2 release).
- Consideration for carrying out a gas dispersion study to understand the dispersion profile of a cold dense CO_2 cloud and to use those results to establish some form of safety zone during LCO_2 offloading operations, if deemed necessary.
- Consideration for carrying out a quantitative risk assessment (QRA) to understand to understand the risk of sensitive receptors (i.e., residential population, industrial population, etc.)
- Consideration for gas detector provisions where personnel are expected to be present. Some examples raised were enclosed spaces such as machinery spaces or accommodation where CO_2 may enter the ventilation air intakes. It was also discussed that placing gas detectors at the offloading manifold for early detection of a leak may not be effective given that the cargo manifold is located on an open deck.
- Consideration for closed circuit television (CCTV) provisions around the manifold area to allow for remote monitoring and to minimise the need for personnel to be present.

Apart from dispersion concerns, another possible concern raised with a loss of containment of LCO_2 was with regards to the depressurization of LCO_2 upon release to atmosphere which rapidly expands, thus bringing down the fluid/gas temperature below the release temperature. This is also known as the Joule-Thomson Expansion effect where formation of dry ice may occur which poses an embrittlement concern to the equipment and structure in the vicinity of the release. To further understand the extent of such a consequence, a recommendation was raised to evaluate the various scenarios of pressurized LCO_2 release towards ambient pressure to understand the extent of formation of cold temperature zones.

Operational Aspects

There were several operational concerns raised for the various LCO_2 offloading concepts, with the common ones related to pre / post offloading activities. Prior to each offloading, the LCO_2 offloading system is required to be free of moisture to prevent icing of remnant moisture which could lead to blocked discharge and subsequent over-pressurisation. As it was unclear what type of medium should be used, given that the most common medium (dry air) poses an impurity issue due to high N_2 content which is non-condensable, a recommendation was raised to ensure that the LCO_2 offloading system is dried by blowing a suitable medium.

After each offloading operation, the LCO_2 offloading system needs to be purged to ensure that there is no remnant LCO_2 present in the offloading arm / hose prior to disconnection. However, it was uncertain if the pressure of the purge gas is sufficient to empty the lines for a MP system. As such, a recommendation was raised to ensure that there is sufficient pressure difference between the purge gas and the receiving tank pressure during post offloading operations or provide equivalent measures to ensure complete purging of the LCO_2 lines and offloading arm / hose. An additional recommendation was also raised to evaluate further on the requirements of purging for the bulk liquid terminal manifolds with the concern relating to the presence of remnant LCO_2 in the long stretch of piping onshore that connects the terminal jetty to the storage tank.

Feasibility Aspects

While impurities in LCO_2 was raised as a safety concern in the earlier discussions, it was also highlighted as a potential feasibility issue that needs to be addressed for OCCS to be readily adopted, as end-users may have a strict tolerance for impurities, depending on the processes they are intending to use CO_2 for. Furthermore, the storage conditions of LCO_2 may vary depending on the amount of impurities present which may limit the type of LCO_2 specifications a receiving vessel or receiving terminal may receive due to their existing design considerations. Therefore, in addition to the recommendation to develop standards for OCCS, it was highlighted as well that further communication needs to be established between the end-users and statutory boards to better define the impurity limits as various end-user receiving terminals may have different requirements for the amount of impurities present.

The abovementioned concern is even more apparent for concept 4 which involves swapping of LCO_2 ISO tank containers at the container terminal. Due to a logistics reality, the container terminal may not have designated ISO tank containers meant for specific ISO tank container types and their connections as the container terminal is expected to receive all types of container ships with different type of OCCS for different type of fuels resulting in varying impurity levels in the LCO_2. It is expected that a different empty LCO_2 ISO tank container will be loaded onto the containership which may result in mixing of different LCO_2 specifications that may not be suitable for that particular container ship's OCCS. Therefore, a recommendation was raised to consider designating the ISO tank containers at the container terminal that are suitable for specific fuel types.

It shall also be noted that a recommendation was raised to highlight the concern with regards to the holding time of BOG within each ISO tank container (estimated to be 30-90 days), given that a containership is expected to have 10-15 LCO_2 ISO tank containers onboard and will only carry out the tank swapping when all the ISO tank containers are full of LCO_2.

From the above discussions, it can be seen that the various LCO_2 offloading concepts are still conceptual in nature with a number of assumptions required to be made such as the design considerations, end-user demand/requirements, location of application, etc. The HAZID team felt that these assumptions will undoubtedly have an impact on the risk ranking and agreed that it would be more appropriate to have the risk ranking carried out by dedicated project teams who are taking these LCO_2 offloading concepts forward to the next phase. Therefore, risk ranking was not carried out during this HAZID.

The full list of recommendations is detailed in the following section, with the full HAZID worksheet documenting the causes, consequences and associated safeguards attached in Error! Reference source not found..

7.1.6.2 Recommendations

There were a total of 54 recommendations made during the HAZID workshop which are detailed in Table 7.5 below.

Table 7.5 – HAZID recommendations

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
1. Consider optimising the location of the vent mast to minimise the toxic effect of CO_2 dispersion to personnel.	Consequences: 1.1.1.2.2, 1.4.2.1.2, 2.6.4.2.1, 3.1.1.2.2, 3.4.2.1.2, 4.6.4.2.1, 8.4.2.1.1	Concept 1, 2, 3 and 4	
2. In the event where there is a demand for venting CO_2 to vent mast, procedures and measures (i.e., cordoning or restriction zones) need to be in place to ensure that personnel will not be in the vicinity of the vent mast. Concern relates to vent mast being uninsulated and the icing phenomenon may cause frostbite to personnel	Consequences: 1.1.1.2.2, 1.4.2.1.2, 3.1.1.2.2, 3.4.2.1.2	Concept 1, 2 and 3	
3. Consider providing remote isolation arrangements on the LCO_2 tank PSVs to prevent excessive depressurization on the LCO_2 tank in the event where the PSV takes a longer than required time to be closed. Isolation arrangements may bring about concerns with inadvertent closure of isolating valves inhibiting the function of PSVs	Consequences: 2.6.4.1.1, 2.6.4.2.1, 2.6.4.2.2, 4.6.4.1.1, 4.6.4.2.1, 4.6.4.2.2	Concept 1, 2 and 3	
4. Carry out a compatibility assessment between the merchant vessel and LCO_2 receiving vessel for the ship-to-ship LCO_2 offloading operation. A compatibility assessment usually looks at multiple aspects of the transfer operation (i.e., mooring loads/arrangement, weather profile at the shortlisted locations, berthing and fendering requirements, alignment of vessels, type of transfer equipment - loading arm or hoses, location of cargo transfer manifold, vapour return capabilities, purging capabilities, design pressure, operational & safety philosophy, etc.)	Consequences: 1.1.1.3.3, 1.5.1.1.1, 2.1.1.2.1, 2.1.1.2.2, 2.6.1.2.1, 2.6.1.3.1, 2.9.2.2.1, 2.9.5.1.1, 4.9.2.2.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
5. To take into account future demand for LCO_2 offloading into the local port's expected vessel traffic calculation to ensure that sufficient resources are made available to tend to any emergencies	Consequences: 1.3.1.1.1, 3.3.1.1.1, 8.3.1.1.1	Concept 1, 2, 3 and 4	
6. Consider tapping onto the existing OCCS' reliquefaction system onboard the vessel.	Consequences: 1.4.2.1.1	Concept 1, 2 and 3	
7. Develop LCO_2 transfer procedures which covers StS and Ship-to-Shore aspects. Concern relates to unfamiliarity with StS operations for some merchant vessels	Consequences: 1.5.1.1.1, 1.5.2.1.1	Concept 1, 2 and 3	
8. Ensure that pre-cooling capabilities are provided in design as pre-cooling should be carried out prior to LCO_2 transfer (especially in tropical countries). Concern relates to excessive vaporization of LCO_2 which may generate overpressure concerns.	Consequences: 2.1.1.1.1, 2.1.1.1.2, 4.1.1.1.2, 4.1.1.1.3	Concept 1, 2 and 3	
9. Ensure that LCO_2 transfer procedures are developed which should include pre-cooling as a step prior the actual LCO_2 transfer operations	Consequences: 2.1.1.1.2, 4.1.1.1.3	Concept 1, 2 and 3	
10. Consider to provide ship-to-ship and ship-to-shore links which will ensure that offloading pumps will be tripped in the event of any ESD activation on LCO_2 receiving vessel/facility side or upon breakaway of offloading hoses/arms.	Consequences: 2.1.1.2.1, 2.6.1.2.1, 2.6.1.3.1, 2.6.1.3.2, 2.6.3.1.1, 2.7.1.1.1, 2.7.1.2.1, 2.9.2.2.1, 4.1.1.2.1, 4.6.1.2.1, 4.6.1.3.1, 4.6.1.3.2, 4.6.3.1.1, 4.7.1.1.1, 4.9.2.2.1, 7.3.1.1.1, 7.3.1.1.2	Concept 1, 2 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
11. Consider providing vessel separation device which will provide a quicker ESD response	Consequences: 2.1.1.2.1, 4.1.1.2.1	Concept 1, 2 and 3	
12. Consider providing gas detectors (CO_2 detectors) where personnel are expected to be present (i.e., machinery spaces, accommodation, etc.). It shall be noted that gas detectors that are placed out in the open deck/areas may not be as effective due to natural ventilation.	Consequences: 2.1.1.2.1, 2.5.1.2.1, 2.6.1.1.1, 2.6.1.2.1, 2.6.1.3.1, 2.9.2.2.1, 4.1.1.2.1, 4.5.1.2.1, 4.6.1.1.1, 4.6.1.2.1, 4.6.1.3.1, 4.9.2.2.1	Concept 1, 2 and 3	
13. Consider carrying out a gas dispersion study to understand the dispersion profile of a dense gas CO_2 cloud (since CO_2 is denser than air and will be cold)	Consequences: 2.1.1.2.1, 2.2.1.1.1, 2.2.1.1.2, 2.6.4.1.1, 2.6.4.2.1, 2.6.4.2.2, 4.1.1.2.1, 4.2.1.1.1, 4.2.1.1.2, 4.6.4.1.1, 4.6.4.2.1, 4.6.4.2.2, 8.4.2.1.1, 9.1.2.1.1	Concept 1, 2, 3 and 4	
14. Consider providing elastic mooring pennants for the mooring equipment	Consequences: 2.1.1.2.3, 4.1.1.2.3	Concept 1, 2 and 3	
15. Consider establishing safety zones for LCO_2 offloading based on gas dispersion results, if necessary	Consequences: 2.2.1.1.2, 4.2.1.1.2	Concept 1, 2 and 3	
16. Ensure that vibrational related impact from the proposed location of LCO_2 offloading systems (for marine vessels) is taken into consideration during design. Concern relates to possible close proximity to engine room.	Consequences: 2.6.1.1.1, 4.6.1.1.1	Concept 1, 2 and 3	
17. Consider carrying out inspections for the LCO_2 pipelines during dry-docking where possible	Consequences: 2.8.1.1.1, 4.8.1.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
18. Evaluate possibility of implementing spill containment system for the LCO_2 offloading system (some examples would be flange/splash guards) to minimise propagation of LCO_2 release	Consequences: 2.6.1.1.2, 4.6.1.1.2	Concept 1, 2 and 3	
19. Consider providing stand-by pressurised firehose to provide deluge by spraying down the deck to minimise direct contact of LCO_2 to the bare steel	Consequences: 2.6.1.1.2, 4.6.1.1.2, 8.4.1.1.2, 9.1.1.1.2, 9.1.1.2.2	Concept 1, 2 and 3	
20. Carry out a compatibility assessment between the LCO_2 receiving vessel and bulk liquid terminal for the ship-to-shore LCO_2 offloading operation. A compatibility assessment usually looks at multiple aspects of the transfer operation (i.e., mooring loads/arrangement, weather profile at the shortlisted locations, berthing and fendering requirements, alignment of vessels, type of transfer equipment - loading arm or hoses, location of cargo transfer manifold, vapour return capabilities, purging capabilities, design pressure, operational & safety philosophy, etc.).	Consequences: 3.1.1.3.3, 3.5.1.1.1, 4.1.1.2.1, 4.1.1.2.2, 4.6.1.2.1	Concept 1, 2 and 3	
21. Evaluate the scenario of pressurised LCO_2 release towards ambient pressure to further understand the extent of formation of cold temperature zones. Concern relates to depressurization of LCO_2 (rapid expansion) which brings down the fluid/gas temperature below the release temperature, which is also known as the cooling effect from Joule-Thomson Expansion. Depending on the rate of expansion, there may be a possibility that the pressure and temperature will drop below the triple point and hence, formation of dry ice.	Consequences: 2.6.1.1.2, 4.6.1.1.2, 8.4.1.1.2, 9.1.1.1.2, 9.1.1.2.2	Concept 1, 2, 3 and 4	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
22. Prior to any LCO_2 transfer operations, drip trays should be emptied. Reference should be made to SIGTTO guidance	Consequences: 2.5.1.2.1, 4.5.1.2.1	Concept 1, 2 and 3	
23. Consider providing water spray curtain on the manifold area for the merchant vessel / receiving vessel which will help to protect against low temperature embrittlement damage. However, concern with regards to potential formation of carbonic acid if LCO_2 is dissolved in water which poses acidity and possible corrosion issues to material.	Consequences: 2.6.1.1.2, 4.6.1.1.2	Concept 1, 2 and 3	
24. Sizing of the drip tray should be calculated in the detailed stages of the Project which would depend on the expected LCO_2 offloading rates, as well as taking into consideration some of the safeguards (i.e., ESD, SSL, etc.)	Consequences: 2.9.3.1.1	Concept 1, 2 and 3	
25. Ensure that manual handling related concerns associated with portable drip trays are addressed once the sizes are determined.	Consequences: 2.9.3.1.1	Concept 1, 2 and 3	
26. Remote monitoring is preferred for the offloading operations due to asphyxiation and cold burn concerns	Consequences: 2.6.1.2.1, 2.9.2.2.1, 4.6.1.2.1, 4.9.2.2.1	Concept 1, 2 and 3	
27. Consider providing CCTVs on the manifold area to allow for remote monitoring, minimising the need for personnel to be present	Consequences: 2.6.1.2.1, 2.9.2.2.1, 4.6.1.2.1, 4.9.2.2.1	Concept 1, 2 and 3	
28. Evaluate if recirculation of LCO_2 on the merchant ship through the recirculation line and spray headers is an effective means of safeguard to increase pressure within the LCO_2 tank to prevent vacuum conditions	Consequences: 2.6.1.3.2, 2.7.1.2.1	Concept 1, 2 and 3	
29. Develop a detailed transfer process between LP and MP systems (for both ship-to-ship and ship-to-shore).	Consequences: 2.6.2.1.2, 2.6.2.1.3, 2.7.1.1.1, 4.6.2.1.2, 4.6.2.1.3, 4.7.1.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
Concern relates to LP/MP interface issues which may result in over-pressurisation concerns			
30. Ensure safeguards are provided on the LCO_2 receiving vessel in the case of operating on LP/MP LCO_2 and returning vapour back to a LP/MP LCO_2 merchant vessel. This recommendation should be addressed together with Rec #29.	Consequences: 2.6.2.1.2, 2.6.2.1.3	Concept 1, 2 and 3	
31. Consider providing a heater on the booster pump discharge of the merchant vessel to send on-spec LCO_2 to the receiving vessel	Consequences: 2.6.2.1.1	Concept 1, 2 and 3	
32. Develop and establish an emergency response plan for all vessels/terminal in the event of any LCO_2 release during offloading operations.	Consequences: 2.6.3.1.2, 4.6.3.1.2	Concept 1, 2 and 3	
33. Prior to any LCO_2 offloading operations, ensure that the offloading system are dried by blowing a suitable medium which will need to be assessed further (some examples raised are using CO_2). Concern relates to impurities from using dry air due to the high N_2 content which is non-condensable.	Consequences: 2.9.2.2.1, 4.9.2.2.1, 9.3.1.3.1	Concept 1, 2, 3 and 4	
34. Ensure that there is sufficient pressure difference between the purge gas and the receiving tank pressure especially for MP conditions during post offloading operations, or provide equivalent measures to ensure complete purging of the LCO_2 lines, offloading hose/arm.	Consequences: 2.9.5.1.1, 4.9.4.1.1, 6.1.2.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
Concern relates to inability to push remnant LCO_2 into the MP LCO_2 receiving tank. Some other options discussed are to heat up and vaporize the remnant LCO_2.			
35. Standards need to be developed for OCCS that are planned to be installed onboard merchant ships/tankers/containerships to standardise the amount of impurities present in the captured CO_2 or LCO_2 prior to transfer to LCO_2 receiving vessel or storage. Reference could be made to standards around EGCS requirements as well. Further communication needs to be established between the end-users and statutory boards to better define the impurity limits as various end-user receiving terminals may have different requirements for the amount of impurities present	Consequences: 4.9.2.1.1, 9.3.1.1.1, 9.3.1.2.1	Concept 1, 2, 3 and 4	
36. Develop cargo operation manual that should cover all operational related issues highlighted in the HAZID, including purging post offloading/unloading.	Consequences: 2.9.5.1.1, 4.9.4.1.1, 6.1.2.1.1, 9.3.2.1.1	Concept 1, 2, 3 and 4	
37. Reference should be made to SIGTTO for safety related issues for both vessel side and terminal side	Consequences: 4.1.1.2.1	Concept 1, 2 and 3	
38. Consider carrying out a QRA to understand to understand the risk of sensitive receptors (i.e., residential population, industrial population, etc.)	Consequences: 4.2.1.1.1, 4.2.1.1.2	Concept 1, 2 and 3	
39. Consider providing a heater on the booster pump discharge of the receiving vessel to send on-spec LCO_2 to the bulk liquid terminal.	Consequences: 4.6.2.1.1	Concept 1 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
40. Ensure safeguards are provided on the onshore terminal in the case of operating on LP/MP LCO_2 and returning vapour back to a LP/MP receiving vessel. This recommendation should be addressed together with Rec #29.	Consequences: 4.6.2.1.2, 4.6.2.1.3	Concept 1 and 3	
41. Provide filters or strainer for the LCO_2 receiving vessel offloading pumps or bulk liquid terminal/bulk storage facility unloading pumps. Concern relates to impurities that may be present as the receiving vessel/bulk liquid terminal/bulk storage facility is anticipated to receive multiple specs of LCO_2.	Consequences: 4.9.2.3.1, 9.3.1.4.1	Concept 1 and 3	
42. Carry out a compatibility assessment between the tanker and bulk liquid terminal for the ship-to-shore LCO_2 transfer operation. A compatibility assessment usually looks at multiple aspects of the transfer operation (i.e., mooring loads/arrangement, weather profile at the shortlisted locations, berthing and fendering requirements, alignment of vessels, type of transfer equipment - loading arm or hoses, location of cargo transfer manifold, vapour return capabilities, purging capabilities, design pressure, operational & safety philosophy, etc.)	Consequences: 6.1.1.1.1, 6.1.2.1.1	Concept 1	
43. Evaluate further on the requirements of purging for the bulk liquid terminal side manifold. Concerns relate to remnant LCO_2 present in the long stretch of piping onshore from terminal jetty to storage tank which may be a significant distance away.	Consequences: 4.9.4.1.1, 6.1.2.1.1	Concept 1 and 3	
44. Ensure that adequate training is provided for the crew operating LCO_2 offloading systems. This recommendation is more relevant for merchant	Consequences: 2.1.1.1.2, 2.6.1.2.1, 2.6.1.3.1, 2.6.2.1.2,	Concept 1 and 3	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
ships as the crew on these vessels (other than gas carriers) are probably not involved in any liquefied gas transfer operations in their lifetime of operations.	2.6.2.1.3, 2.6.3.1.1, 2.6.4.1.1, 2.6.4.2.1, 2.6.4.2.2, 2.7.1.2.1, 2.9.2.2.1, 2.9.5.1.1, 4.6.1.1.1, 6.1.1.1.1, 6.1.2.1.1		
45. Ensure that offloading operations from LCO_2 receiving vessel to FCSU should be directed to a different tank that is intended to be used for offloading operations from FCSU to end-users. Concern relates to possibility of greater outgoing flow from the same FCSU LCO_2 tank resulting in vacuum conditions. It shall also be noted that: 1) As reference, for vessels that are able to receive cargo and utilise cargo concurrently (i.e., FSRUs), the LNG that is transferred from a LNGC is directed to a different tank from the tank that is supplying LNG for regasification purposes. 2) Regardless of the outgoing flow, there shall be no increase in the offloading flow from the LCO_2 receiving vessel (i.e., operating more offloading pumps) outside of intended operating envelope as there will be a risk of pulling vacuum on the receiving vessel tanks.	Consequences: 7.3.1.1.1, 7.3.1.1.2	Concept 2	
46. In the event if concurrent loading/offloading to/from a same LCO_2 tank on the FCSU is deemed possible or practical for the nature of intended use, measures need to be put in place to ensure that the storage conditions remain unaffected in the LCO_2 tank. Concern relates to rapidly changing storage conditions within the affected LCO_2 tank which may fall below the triple point and result in solidification.	Consequences: 7.3.1.1.2	Concept 2	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
47. Ensure that gas detectors (CO_2 detectors) will be provided across the vessel where LCO_2 ISO tank containers are expected to be stored	Consequences: 8.4.1.1.1	Concept 4	
48. Ensure that personnel who will be involved with the manual connection/securement of the LCO_2 ISO tank container onto the truck, will need to have appropriate PPE (including portable gas detectors). Depending on the restrictions of container terminals/bulk storage facilities globally, if there are no dedicated areas for unloading LCO_2 ISO tank containers, there may not be provisions for permanent fitted gas detectors for the truck loading/unloading bay.	Consequences: 8.4.1.1.1, 9.1.1.1.1, 9.1.1.2.1, 9.1.2.1.1	Concept 4	
49. Consider mis-directed flow of LCO_2 due to mis-connection at the truck manifold in the facility's HAZOP	Consequences: 9.1.1.2.1	Concept 4	
50. PBU option is preferred as compared to having the minimum recirculation line. Concern relates to the effectiveness of maintaining the ISO tank container pressure by relying on the minimum recirculation line	Consequences: 9.1.1.5.1	Concept 4	
51. For adoption of Concept 4 in colder climates, attention needs to be given to the difference in ambient temperature and the LCO_2 ISO tank container to ensure that the ISO tank container will not face a vacuum condition during unloading. Concern relates to insufficient vaporisation due to low delta in temperature resulting in vacuum conditions.	Consequences: 9.2.1.1.1	Concept 4	

Recommendation	Place(s) used in HAZID worksheet	Applicability to Concept 1, 2, 3, 4	Comments
52. Consider designating the ISO tank containers that are suitable for specific fuel types, to minimise amount of different impurities present in the ISO tank containers.	Consequences: 9.3.1.2.1	Concept 4	
53. The intended design of the ISO tank container should be able to handle BOG up to 30-90 days. However, there are at least 10-15 ISO tank containers on the container ship whereby the LCO_2 ISO tank containers swapping will most likely only take place when all ISO tank containers onboard the container ship are full with LCO_2. Concern relates ISO tank containers being in a full condition exceeding 30-90 days which may result in an over-pressurisation risk.	Consequences: 9.3.1.2.1	Concept 4	
54. Develop a detailed transfer process between onboard carbon capture system and the ISO tank container. Concern relates to over-pressurisation due to remnant LCO_2 and associated pressure	Consequences: 9.3.3.1.1	Concept 4	

7.2 Simultaneous Operations (SIMOPS)

7.2.1 Overview

A SIMOPS workshop was conducted as part of the "Concept Study to Offload Onboard Captured Carbon Dioxide". The workshop was held remotely from 18th – 19th October 2023 via videoconference means involving members of GCMD, LR/Arup and a number of industry study partners from diverse backgrounds who provided a wealth of experience and expertise during the SIMOPS discussions.

The aim of the SIMOPS study was to assess and understand the impact of carrying out all possible concurrent activities alongside LCO_2 offloading operations that were shortlisted previously (See Chapter 3).

A total of 35 scenarios were identified, with a number of concerns that are related mainly to the safety and operational aspects of carrying out concurrent activities with LCO_2 offloading operations. The list of the concerns and applicability to each of the LCO_2 offloading concepts is summarised in the table below.

Table 7.6 – List of concerns and applicability to each LCO_2 offloading concept (SIMOPS)

List of Concerns	Applicability to LCO2 offloading concepts (Y/N)			
	Concept 1	Concept 2	Concept 3	Concept 4
Potential for dropped objects from concurrent activities. This may result in damage of the LCO_2 offloading equipment and pipeline while LCO_2 transfer is in progress, leading to a subsequent loss of LCO2 containment. Dropped objects and loss of LCO_2 containment will also be a risk for the personnel involved in the SIMOPS.	N	Y	Y	N
Loss of containment of LCO_2 during LCO_2 offloading operations affecting other concurrent activities in the vicinity	Y	Y	Y	N
Loss of containment of alternate fuels bunkering (i.e., LNG/LPG) during simultaneous fuel bunkering which may affect concurrent LCO_2 offloading operations	Y	Y	Y	N
Manpower designation and distribution in the event if multiple StS operations are carried out at the same time	Y	Y	Y	N

Although the SIMOPS discussion were for all four offloading concepts, it should be noted that majority of the discussions only apply to concept 1, 2 and 3. As for concept 4, the current regulations, such as the IMDG code classifies CO_2 a non-flammable, non-toxic gas. Many terminals handle LCO_2 ISO tank containers as ordinary containers during transfers. Consequently, there are no significant impact or concerns regarding concurrent operations when LCO_2 ISO tank containers are being transferred. The transfer operation is considered the same as that for other ordinary containers. The offloading of LCO_2 from the ISO tank containers at the bulk storage facility is also considered a normal operation for the storage terminal. The requirements for SIMOPS for storage terminals vary based on the chemicals/materials they are storing, which will be covered by their own set of terminal operating procedures. Hence, the LCO_2 offloading aspects of concept 4 were not further assessed.

In total, there were 20 recommendations raised throughout the SIMOPS addressing the abovementioned concerns, which should be taken forward in the next phase of the project or should be considered by interested parties that are further developing OCCS/ LCO_2 offloading concepts.

7.2.2 Aim

The aim of the SIMOPS study was to assess and understand the impact of carrying out all possible concurrent activities alongside LCO_2 offloading operations.

7.2.3 Scope of Work

The scope of work for the SIMOPS was limited to brainstorming the possible activities that can be done in concurrence with LCO_2 offloading operations for the shortlisted LCO_2 offloading concepts, and identifying any additional hazards arising from these activities that may have an impact on the LCO_2 offloading activities. The battery limits for this Project were from the LCO_2 offloading tank onboard the vessel to the LCO_2 storage tank/facility onshore.

The general design envelopes for offloading scenarios are shown in Table 2.27.

The shortlisted concepts are:

- Concept 1 – Ship-to-liquid bulk terminal, as described in Section 3.3.2.
- Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel, as described in Section 3.3.3.
- Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel, as described in Section 3.3.4.
- Concept 4 – Ship-to-terminal with ISO tank containers, as described in Section 3.3.5.

Note: Hazards associated with LCO_2 offloading and the various offloading concepts have been covered in the HAZID session

7.2.4 Typical Steps of an Offloading Cycle

The steps typically associated with an offloading cycle are described in Section 7.1.4.

7.2.5 SIMOPS Study

7.2.5.1 SIMOPS Objectives

The objectives of the SIMOPS Study were to:

- Identify the various credible simultaneous operations and the additional hazards arising from those operations that may impact the LCO_2 offloading system
- Understand reasonably foreseeable consequences for the hazards identified
- Review existing prevention/mitigation safeguards and control measures to ensure suitability and understand what additional measures could be taken to eliminate or reduce the level of risk further, following as low as reasonably practicable (ALARP) principles, the detection and control of potential issues as well as suitable emergency response
- Create a record of actions and recommendations for further supplementary work

- Serves as an input to the Matrix of Permitted Operations (MOPO) which classifies the various identified simultaneous operations as "Permitted", "Conditional" or "Restricted" depending on the SIMOPS review [Note 1]

Note 1: Matrix of Permitted Operations (MOPO) is not carried out within this study as the project is still in a conceptual phase, but should be considered to be carried out before the offloading concepts are in operation.

7.2.5.2 SIMOPS Methodology

A SIMOPS study takes on a similar approach as a Hazard Identification (HAZID) study which is a methodical 'creative brainstorming' technique used to identify hazards and operational issues associated with a design, process and / or operation.

A guideword-based technique to identify hazards was used based upon LR experience with guidance from the following sources:

BS ISO 31000: 2018, Risk Management – Principles and Guidelines. [1]

BS ISO 31010: 2019, Risk Management – Risk Assessment Techniques. [2]

The workshop was facilitated and scribed by a LR Risk Specialist.

Guidewords described in Section 7.2.3.7 were applied, initiating and encouraging discussions on possible events that may lead to unplanned outcomes. These prompts are based upon previous experience and indicate the types of hazards that are thought to be applicable to the modalities.

Identification of hazards and causes

Possible hazards were identified by applying the guidewords. If a credible potential hazardous event was identified the SIMOPS team considered possible causes that may lead to this. If no meaningful hazards or causes were identified this was recorded in the minutes.

Evaluation of consequences

The consequences of each cause analysed by the SIMOPS team was assessed to see if the unplanned incident could lead to harm to persons, the consequences of which were discussed and recorded.

Evaluation of safeguards

The SIMOPS team considered the safeguards that are present (or proposed) to see if they provide sufficient protection.

Recommendations

The final stage of the study was to review the list of recommendations that have been raised to ensure that they are clear and have responsible persons assigned to them [Note 2].

Note 1: In the case for this project which is in a conceptual phase, these recommendations are actions that should be taken forward in the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

7.2.5.3 Assumptions

The SIMOPS study shall assume the following:

- Concept 3 was selected as the representative scenario as it is the most complex out of the four concepts, involving StS LCO_2 offloading at anchorage and subsequently Ship-to-Shore LCO_2 offloading at terminal. Bulk of the discussion for concept 3 was expected to be applicable for the other concepts, given the similarities in the transfer approach, or the LCO_2 offloading processes. As such, concept 1 and 2 were done by-difference to concept 3.
- For the various concepts, both LP and MP operating pressures were discussed (where applicable) as they each present their own set of risk.
- Only single failures were considered, i.e., multiple failures were not considered credible, unless they can go undetected (hidden failures).
- The systems, equipment and layout were as per the information shared prior to the SIMOPS workshop.
- The proposed / intended safeguards shall be installed and function as outlined.

7.2.5.4 Team Members

The SIMOPS team comprises the following:

Table 7.7 – SIMOPS team

Name	Role	Organisation	Title	18 Oct 23	19 Oct 23
Nelson Loo	Facilitator	LR MPS	Risk Specialist	Y	Y
Sun-Joo Choi	SME	LR MPS	Senior Risk Specialist	N	N
Brijesh Tewari	SME	LR MPS	Lead Maritime Decarbonisation Consultant	Y	Y
Etemad Hamid	SME	LR	Global Gas Technology Specialist	Y	Y
Cossel Chang	SME	ARUP	Associate Maritime Engineer	Y	N
Lydia Green	SME	ARUP	Ports & Maritime Engineer	N	N
Mark Button	SME	ARUP	Associate Engineer	N	N
Victor Pang	SME	GCMD	Senior Associate	Y	Y
Rashim Berry	SME	EPS	Senior Advisor, Special Projects	N	N
Capt. Suraj	SME	EPS	General Manager, Operations	N	N
Capt. Anish Saxena	SME	EPS	Assistant Operations Manager	Y	N
Nishudhan Ravi	SME	EPS	Assistant Operations Manager	N	N
Ganapathy Vishwanath	SME	EPS	Operations Superintendent	Y	N
Ker Hong Yeow	SME	MISC	Decarbonisation, New Energy & Decarbonisation	N	Y
Kim Sang Su	SME	MISC	Project manager - Floating CO_2 Storage Unit (FCSU) concept engineering	N	N

Name	Role	Organisation	Title	18 Oct 23	19 Oct 23
Kenneth George Ng	SME	MISC	Head Zero Emissions Vessel Project	Y	Y
John Baptist	SME	MISC	Head of Decarbonisation	N	N
Prabagaran Balasundaram	SME	AET-Tankers	Chartering Manager	Y	Y
Nasran Abdullah	SME	AET-Tankers	Marine Engineer, New Energy & Decarbonization	Y	Y
Meninderjit Singh Muktiar Singh	SME	Eaglestar	Manager, Zero Emissions	Y	N
Françoise van den Brink	SME	Port of Rotterdam	Sr. Advisor Energy Transition	N	Y
Royen Gultom	SME	Seatrium	Assistant Process Manager	Y	N
Jei Rollicer Bagonoc	SME	Seatrium	Process Engineer	Y	N
Thomas Sim	SME	Jurong Port	Lead Engineer, Energy Terminals - Energy Transition	Y	Y
Puneet Verma	SME	Chevron	Senior LNG Ship Shore Interface Advisor- Marine Terminals	N	N
Gary Pang	SME	GASPL	Executive Director	N	Y
Amar Chandiram	SME	Shell	Manager	Y	N
Ryo Miyoshi	SME	K-Line	Manager, GHG Reduction Strategy Team	N	Y
So Kah Meng	SME	EMF	Sustainable Energy Manager	Y	Y
Kee Tuan Sian	SME	ZICOM	Vice President	N	Y

7.2.5.5 SIMOPS Nodes

The SIMOPS covered the following nodes:

Table 7.8 – SIMOPS nodes

Nodes	Description
Concept 3, Two-stage ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel	
1	Transit, berthing & mooring of ship-to-LCO_2 receiving vessel
2	LCO_2 transfer to LCO_2 receiving vessel (StS)
3	Transit, berthing & mooring of LCO_2 receiving vessel at bulk liquid terminal
4	LCO_2 offloading to bulk liquid terminal (ship-to-shore)
5	Unmooring and departure of LCO_2 receiving vessel
Concept 1, Ship-to-liquid bulk terminal	
6	Node will be assessed by-difference to concept 3
Concept 2, Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel	
7	Node will be assessed by-difference to concept 3
Concept 4, Ship-to-Terminal with ISO tank containers	
8	Unloading of LCO_2 ISO tank containers from ship-to-shore
9	Transfer from LCO_2 ISO tank containers to storage at bulk liquid terminal

7.2.5.6 List of Possible Concurrent Activities

Example of activities that may have a direct/indirect impact on LCO_2 offloading operations if carried out in parallel are listed below:

- Cargo handling
- Container loading/unloading
- Passenger and crew embarking/disembarking
- Dangerous goods loading/unloading
- Chemical products handling
- Bunkering of fuels
- Ballasting operations
- Gangway & mooring line operation
- Maintenance activities (which include construction, testing and inspection)

It shall be noted that the list of activities above served as a prompt during the SIMOPS workshop and was not meant to limit the discussions to these activities only.

7.2.5.7 SIMOPS Prompts / Guidewords

For the above examples of concurrent activities, the following prompts/guidewords listed below were applied to discuss the hazards arising from the possible concurrent activities and how it may have an impact on the LCO_2 offloading operations.

- Loss of containment (Leakage, overfilling, etc.)
  - Low Temperature hazards
  - Flammable hazards
  - Toxic hazards
  - Asphyxiation hazards
- High pressure hazards
  - Pressurised release of hydraulic oil, etc.
- Utility failure hazards
  - Instrument air, inert gas, hydraulic power, heating/cooling medium and compressed air
- Ventilation failure hazards
- Flooding hazards
- Dropped object hazards
- External fire hazards
- Corrosion / erosion hazards
- Layout hazards (e.g. access/egress, maintenance access and escape)
- Others (e.g. weather, human error, electric/control system failure, etc.)

7.2.5.8 Characteristics of CO_2

The characteristics of CO_2 have been detailed in Section 1.2.

7.2.5.9 Hazards Associated with CO_2

The hazards associated with CO_2 have been detailed in Section 1.4.

7.2.5.10 Documents Reviewed

The HAZID workshop was based on the following documents that were provided pre-HAZID.

Table 7.9 – Documents reviewed

Document No.	Description	Rev
2301-66993 – Part A	Concept Study to Offload Onboard Captured Carbon Dioxide (Part A: Onboard Storage of Captured Carbon Dioxide)	0

Document No.	Description	Rev
2301-66993 – Part B1	Concept Study to Offload Onboard Captured Carbon Dioxide (Part B1: Offloading Concepts)	0
2301-66993 – Part B2	Concept Study to Offload Onboard Captured Carbon Dioxide (Part B2: HAZID Worksheet)	0

7.2.6 SIMOPS Results

7.2.6.1 Results Discussion

There were a total of four LCO_2 offloading concepts assessed during the SIMOPS, with concept 3 being selected as the representative concept (with concept 1 and 2 being assessed by-difference) as it covers both the ship-to-ship and ship-to-shore aspects of LCO_2 offloading, while concept 4 was discussed as an independent node as it involves container loading and truck offloading which is a different type of offloading operation.

The SIMOPS team brainstormed a list of possible concurrent activities for each concept and discussed the potential hazards arising from these activities and how it could impact the LCO_2 offloading operations. Hazards and associated consequences arising from the LCO_2 offloading operation itself, which have already been identified during the HAZID, was also discussed during the SIMOPS on how it could impact the concurrent activities as well. A total of 35 scenarios were identified, with a number of concerns that were related mainly to the safety and operational aspects of carrying out concurrent activities with LCO_2 offloading operations, which will be covered in the sections below.

<u>Safety Aspects</u>

For the safety aspects, there were several concerns associated with the possibility of loss of containment of LCO_2 whilst carrying out concurrent activities during LCO_2 offloading operations. One such concern was regarding dropped objects from the concurrent activity on live LCO_2 offloading equipment and piping during LCO_2 offloading in a double-banking arrangement, as concurrent activities such as cargo/goods handling usually requires a lifting crane to facilitate the loading/unloading. This particular concern seemed to be more applicable to bulk carriers, rather than tankers, given the location and expected lifting envelope of the cranes and therefore, recommendations were raised around ensuring that the operating envelopes for the crane do not encroach into live LCO_2 offloading equipment and piping if there is a need to do concurrent cargo handling activities while offloading LCO_2, and consideration for mechanical protection provisions of exposed LCO_2 equipment and piping at the offloading manifold. Specifically for concept 1 where the tankers are carrying out LCO_2 offloading at bulk liquid terminal, the SIMOPS team agreed that there may be a possibility that the tankers will be carrying out concurrent cargo loading/unloading with LCO_2 offloading from the same offloading manifold, given that this is the nature of bulk liquid terminal operations. However, it was further discussed that all lifting operations (i.e., hook-up and line-up of the transfer hoses) would have to be completed for all lines on that particular manifold, with cranes being locked-out-tagged out (LOTO-ed) prior to any commencement of loading/unloading/offloading operations and hence, removing the concern of dropped objects.

The other concern was regarding the safety of the personnel involved in carrying out the concurrent activities in the vicinity of the LCO_2 offloading operations where a loss of containment of LCO_2 may occur from various causes identified during the HAZID. Some of these concurrent activities refer to cargo handling between small dry bulk carriers (usually in the form of a lightering vessel that is significantly smaller than the bulk carrier), bunkering of fuels/alternate fuels and personnel & crew embarkation/disembarkation which involves smaller vessels or personnel working in lower elevations, rendering them susceptible to toxic/asphyxiation hazards associated with LCO_2 release, given that LCO_2 is stored at a refrigerated temperature which will cause a cold dense CO_2 cloud that will tend to stay low and migrate to low points of the vessels. While safeguards associated with preventing or mitigating a loss of containment scenario were addressed in the HAZID, several recommendations were raised during the SIMOPS to address this concern:

- Consideration for carrying out a gas dispersion study to understand the dispersion profile of a cold dense CO_2 cloud and to use those results as additional information for consideration of carrying out concurrent activities alongside LCO_2 offloading operations.
- Ensuring that a briefing/checklist is carried out to notify the small vessel crafts of the potential hazards arising from carrying out concurrent activities with LCO_2 offloading.
- Consideration to provide visual and audio alarm with associated emergency response procedures for crew to react and evacuate in the event of a loss of containment of LCO_2.
- Establishing SIMOPS operational procedures to address the hazards, mitigation and emergency measures associated with loss of containment of LCO_2.
- Establishing emergency preparedness between the parties involved in the concurrent activities while offloading LCO_2.

In addition to loss of containment of LCO_2 during LCO_2 offloading operations, there may also be a possibility of loss of containment of alternate fuels (i.e., LNG/LPG) while carrying out fuel bunkering in concurrence with LCO_2 offloading. While it was discussed that such an operation, if allowed, would be carried out on opposite manifolds, the concern would be on the dispersion of flammable gas during a loss of containment rendering the LCO_2 offloading manifold an unsafe area. As such, a recommendation was raised to check with existing LNG/LPG bunkering safety zone studies to see if the safety zones established encroaches into the LCO_2 offloading systems which will give an indication whether concurrent alternate fuel bunkering can be done with LCO_2 offloading operations.

<u>Operational Aspects</u>

While discussing the impact of carrying out concurrent activities (involving Ship-to-Shore/StS operations) with LCO_2 offloading operations, one main operational concern that was identified was regarding the requirements of designated PIC for each StS operation as well as manpower concerns involved in each StS operation (e.g. cargo transfer and LCO_2 offloading simultaneously). Though it was raised by the SIMOPS team, with reference to LNG bunkering, that concurrent activities such as StS operation is not expected to be allowed while LCO_2 offloading operations are ongoing, it was unclear if that will apply to LCO_2 offloading operations given that LCO_2, while hazardous, is not considered more hazardous than LNG, and is typically not considered the main function of the vessel (i.e., merchant ship adopting OCCS in addition to its own vessel activities and therefore, LCO_2 offloading is considered a secondary function). Therefore, several recommendations were raised to address this concern:

- Clarification on the requirements for designated PIC in the event if multiple StS operations are expected.
- Evaluation on the manpower required for concurrent operations as each operation has its own operating plan which includes mitigative and emergency response.

It shall be noted that the above discussions only apply to concept 1, 2 and 3. As for concept 4, the current regulations (i.e., IMDG code) classifies CO_2 as a non-flammable, non-toxic gases and it is being treated by many terminals as an ordinary container being transferred. In this case, there is no impact or concerns with concurrent operations while LCO_2 ISO tank container is being transferred. That being said, a recommendation was still raised to revisit the SIMOPS risk assessment in the event if there is any update with the IMDG classification of CO_2 from non-toxic to other classifications, given that OCCS and LCO_2 offloading are still considered a novel application to the industry. With regards to the subsequent LCO_2 offloading at bulk storage facility, it was discussed with the SIMOPS team that this offloading operation is considered a normal operation for the storage terminal and also agreed with the SIMOPS team that the requirements for SIMOPS for storage terminals varies based on the chemicals/materials they are storing, and they are covered by their own set of terminal operating procedures. Therefore, the LCO_2 offloading aspects of concept 4 was not further assessed.

The full list of recommendations is detailed in the following section, with the full SIMOPS worksheet documenting the causes, consequences and associated safeguards attached in Error! Reference source not found..

7.2.6.2 Recommendations

There were a total of 20 recommendations made during the SIMOPS workshop which are detailed in Table 7.10 below.

Table 7.10 – SIMOPS recommendations

Recommendation	Place(s) used in SIMOPS worksheet	Applicability to Concept 1, 2, 3, 4	Comments
1. In the event of the need to do concurrent cargo handling operations with LCO_2 offloading operations, ensure that the operating envelope of the cranes used for cargo handling operations do not encroach into the boundaries of the LCO_2 offloading systems	Consequences: 2.1.1.1.1	Concept 1, 2 and 3	
2. Consider providing mechanical protection on the exposed LCO_2 piping and systems at the offloading manifold	Consequences: 2.1.1.1.1	Concept 1, 2 and 3	
3. Consider providing EEBDs in the vicinity in areas that are identified as a risk from CO_2 dispersion.	Consequences: 2.1.2.1.1, 2.2.2.1.1, 2.4.1.1.1, 2.7.1.1.1, 4.3.1.1.1, 4.6.1.1.1, 6.1.2.1.1, 6.3.2.1.1	Concept 1, 2 and 3	
4. Prior to the various concurrent activities (i.e., cargo transfer operation, personnel embarkation/disembarkation, etc.) while doing LCO_2 offloading operation, ensure that briefing/checklist is carried out to notify the various small vessel crafts (that are involved in the other concurrent operations) of the potential hazards that may arise from this SIMOPS operation. Information such as emergency response and mitigation actions should also be provided.	Consequences: 2.1.2.1.1, 2.2.2.1.1, 2.4.1.1.1, 2.7.1.1.1, 4.3.1.1.1, 4.6.1.1.1, 6.1.2.1.1, 6.3.2.1.1	Concept 1, 2 and 3	
5. In the event of the need to do concurrent operations with LCO_2 offloading operations, establish SIMOPS operational procedures to address the hazards, mitigation and emergency measures associated with loss of containment of LCO_2.	Consequences: 2.1.2.1.1, 2.2.2.1.1, 2.4.1.1.1, 2.7.1.1.1, 4.3.1.1.1, 4.6.1.1.1, 6.1.2.1.1, 6.3.2.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in SIMOPS worksheet	Applicability to Concept 1, 2, 3, 4	Comments
6. Consider to provide visual and audio alarm with associated emergency response procedures for crew to react and evacuate in the event of loss of containment of LCO_2.	Consequences: 2.1.2.1.1, 2.2.2.1.1, 2.4.1.1.1, 2.7.1.1.1, 4.3.1.1.1, 4.6.1.1.1, 6.1.2.1.1, 6.3.2.1.1	Concept 1, 2 and 3	
7. Carry out a gas dispersion study for LCO_2 release to identify the extent of CO_2 dispersion profile on the vessel. These results can then be used to provide additional information for consideration of carrying out concurrent activities alongside LCO_2 offloading operations.	Consequences: 2.1.2.1.1, 2.2.2.1.1, 2.4.1.1.1, 2.7.1.1.1, 4.3.1.1.1, 4.6.1.1.1, 6.1.2.1.1, 6.3.2.1.1	Concept 1, 2 and 3	
8. In the event of the need to do concurrent operations with LCO_2 offloading operations which requires vessels to be alongside each other, establish emergency preparedness between the involved parties.	Consequences: 2.1.4.1.1, 2.2.3.1.1, 2.4.3.1.1, 2.7.2.1.1, 4.6.2.1.1, 6.3.3.1.1	Concept 1, 2 and 3	
9. Clarify on the requirements for designated PIC in the event if multiple StS operations are expected. Concern relates to requirement for PIC for tanker StS operations, but it is uncertain if there shall be two PIC for two separate StS operations which also brings up the concern of having two separate workflows for the same ship.	Consequences: 2.2.1.1.1, 2.7.1.1.1, 2.7.1.2.1, 4.6.1.1.1, 4.6.1.2.1, 6.1.1.1.1, 6.3.1.1.1	Concept 1, 2 and 3	
10. Evaluate on the manpower required for concurrent operations as each operation has its own operating plan which includes mitigative and emergency response and is expected to have a dedicated number of crew involved. Concern relates to lack of manpower, fatigue related issues, unclear designation in the event of carrying out concurrent operations with LCO_2 offloading operation.	Consequences: 2.2.1.1.1, 2.7.1.2.1, 4.6.1.1.1, 4.6.1.2.1, 6.3.1.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in SIMOPS worksheet	Applicability to Concept 1, 2, 3, 4	Comments
In the event of any emergency on the vessel, all offloading/transfer operations are expected to be stopped			
11. Ensure that communications channel are established between the LCO_2 receiving vessel, merchant vessel and fuel bunker vessel to alert all parties in the event of LCO_2 loss of containment or activation of the ESD-SSL link between the merchant vessel and LCO_2 receiving vessel.	Consequences: 2.7.1.1.1, 4.6.1.1.1	Concept 1, 2 and 3	
12. Check with existing LNG/LPG bunkering safety zone studies to see if the safety zones established encroaches into the LCO_2 offloading systems which will give an indication whether concurrent alternate fuel bunkering can be done with LCO_2 offloading operations.	Consequences: 2.7.1.2.1, 4.6.1.2.1	Concept 1, 2 and 3	
13. Evaluate further on the interaction between safety systems in the event of carrying out concurrent activities with LCO_2 offloading operations. Concern relates to having two separate ESD systems installed to enable two distinct offloading operations (i.e., bunkering of fuels and LCO_2 offloading), where there is uncertainty over the interaction and testing of ESD activation of either system and cause-effect over total operations.	Consequences: 2.7.1.2.1	Concept 1, 2 and 3	
14. Ensure that consideration should be given to the size of the vessel in relation to the expected amount of LCO_2 being offloaded (~2000m^3) and type of cargos being carried, to determine if there is a need to carry out a ballast operation	Consequences: 2.8.1.1.1, 4.7.1.1.1	Concept 1, 2 and 3	
15. Ensure that ballasting operations plan and sequence developed must be accurate, which takes into consideration of the movement of mass from opposite sides of the vessel.	Consequences: 2.8.1.1.1	Concept 1, 2 and 3	

Recommendation	Place(s) used in SIMOPS worksheet	Applicability to Concept 1, 2, 3, 4	Comments
16. Ensure that Permit-to-Work (PTW) is in place which should cover maintenance activities on the LCO_2 offloading system or in the vicinity of the LCO_2 offloading system	Consequences: 2.10.1.1.1, 2.11.1.1.1, 4.9.1.1.1, 4.10.1.1.1	Concept 1, 2 and 3	
17. Evaluate possibility of implementing spill containment system for the LCO_2 offloading system (some examples would be flange/splash guards) to minimise propagation of LCO_2 release. Concern relates to possible concurrent operations on the same offloading manifold dealing with LCO_2 and other cargo	Consequences: 6.1.2.1.1, 6.3.2.1.1	Concept 1	
18. Apart from the pre-loading/discharging checklist that are already in place to handle the dangerous goods, ensure that concerns associated with static discharge from concurrent LCO_2 offloading operations are also raised and addressed.	Consequences: 6.2.2.1.1	Concept 1	
19. Ensure that calculations have been carried out for the anticipated well injection rates and LCO_2 receiving rates from the LCO_2 receiving vessel to account for the amount of ballast required.	Consequences: 7.1.1.1.1	Concept 2	
20. In the event if there is an update in the IGC Code and IMDG Code for CO_2 to be considered as toxic gas, the SIMOPS risk assessment will have to be revisited to take into consideration of such changes.	Consequences: 8.1.1.1.1	Concept 4	

7.3 Coarse Quantitative Risk Assessment (QRA)

7.3.1 Overview

A coarse QRA study was conducted as part of the "Concept Study to Offload Onboard Captured Carbon Dioxide", with the aim of assessing the overall risk arising from the shortlisted LCO_2 offloading concepts due to toxic gas dispersion, and to also provide comparison with a risk acceptance criteria adapted from UK HSE.

The individual risk contours illustrate the levels of individual risk to a hypothetical person who is present all of the time (24 hours a day, 365 days a year) at a given location. This location specific individual risk (LSIR) contour expresses the risk exposure to any individual, if initially present in a particular area for one whole year or for the full duration of the activity. The risk exposure is calculated for all relevant leak hazards and summed to give the overall risk in particular areas. In the fatality estimation, the consequences of each outcome from an accidental event are represented by the probability of death for an individual initially present in a particular area when the event occurs.

The following table summarises the salient findings of the coarse QRA study for LCO_2 offloading concept 3, which was selected as the representative offloading concept to be assessed.

Table 7.11 – Salient findings of coarse QRA study

Location	Tolerable Risk Criteria	Risk result
Anchorage This is the location where the merchant vessel is expected to offload LCO_2 to the LCO_2 receiving vessel via ship-to-ship transfer	1×10^{-4}/yr for personnel risk. The risk criteria is adapted from the UK HSE ALARP framework whereby risk levels greater than 1×10^{-4}/yr for the public group is considered to be intolerable.	The 1×10^{-4}/yr LSIR contour corresponding to the tolerable risk criteria for personnel onboard vessels or in the vicinity is not reached. Hence, the risk presented is lower than the specified criterion.
Bulk Liquid Storage Terminal This is the location where the LCO_2 receiving vessel is expected to berth to offload LCO_2	1×10^{-4}/yr for personnel risk. The risk criteria is adapted from the UK HSE ALARP framework whereby risk levels greater than 1×10^{-4}/yr for the public group is considered to be in intolerable.	The 1×10^{-4}/yr LSIR contour corresponding to the tolerable risk criteria for personnel onboard the vessel or in the vicinity of the LCO_2 offloading facility is not reached. Hence, the risk presented is lower than the specified criterion.

Given that this is a concept study involving a conceptual design, there are a number of modelling assumptions that were made which affect the overall risk profile of this representative LCO_2 offloading concept. In addition to the modelling assumptions, the selected risk criteria also play an important role in determining the suitability of risk levels arising from the LCO_2 offloading concept. Risk integration with existing facilities' operations is also vital in determining the total risk of the facility that is planning to implement the LCO_2 offloading concept, which should be considered in the next phase of the project or should be considered by interested parties that are further developing OCCS / LCO_2 offloading concepts.

7.3.1 Aim

The aim of the QRA study was to assess the overall risk arising from the shortlisted LCO_2 offloading concepts due to toxic gas dispersion, and to provide comparison with risk acceptance criteria adapted from UK HSE.

7.3.2 Scope of Work

The coarse QRA addressed the shortlisted LCO_2 offloading concepts assessed in the HAZID study which was based on the four selected concepts (chapter 3).

The scope of work for the QRA was limited to toxic releases during the offloading operation and associated offloading equipment. This also included the shore side storage equipment up till the battery limit of the offloading concepts.

The general design envelopes for offloading scenarios are shown in Table 2.27.

The shortlisted concepts are:

- Concept 1 – Ship-to-liquid bulk terminal, as described in Section 3.3.2.
- Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel, as described in Section 3.3.3.
- Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel, as described in Section 3.3.4.
- Concept 4 – Ship-to-terminal with ISO tank containers, as described in Section 3.3.5.

7.3.3 Typical Steps of an Offloading Cycle

The steps typically associated with an offloading cycle are described in Section 7.1.4.

7.3.4 Characteristics of CO_2

The characteristics of CO_2 have been detailed in Section 1.2.

7.3.5 Hazards Associated with CO_2

The hazards associated with CO_2 have been detailed in Section 1.4.

7.3.6 QRA Methodology

7.3.6.1 Study Definition

It is important to clearly define the scope and objectives of the study at its initiation, as this will influence the breadth, depth and the output of the analysis. Study definition involves:

- Definition of the system to be analysed (in terms of the processes involved, the physical boundaries of the system and the nature of the surrounding environment/ population, etc.);
- Describing the reasons for conducting the analysis (the objectives of the study, or the concerns that give rise to the need for the analysis); and,
- Identification of the decisions to be made, using the analysis results as one input. The types of decision to be made influences the output required from the analysis.

7.3.6.2 Data Gathering

Depending on the purpose of the analysis and the size of the system under consideration, the quantity of data required to perform a full QRA can be substantial. Typically, the data required includes:

- Information about the system (engineering drawings, process data, equipment specifications, maps etc.); and,
- Meteorological data.

7.3.6.3 Hazard Identification

The purpose of the hazard identification step is to identify all of the relevant hazards which generate risk within the system, together with how the hazards could be realised. The study definition step may limit the types of hazard of interest. General methods for hazard identification are:

- Review of accident/incident data;
- HAZID studies;
- 'What-If' Analysis;
- The 'Methodical Rupture' approach (listing all potential leak sources from each equipment item within the system); and,
- Use of checklists.

The method used depends on the purpose of the study and the nature of the system under investigation.

7.3.6.4 Risk Screening

In some studies, a risk screening step is performed prior to the full analysis. This could be used to:

- Review the list of hazards obtained at the hazard identification stage and remove any that are not relevant to the current study (e.g. because their effects would be too limited); and/or,
- Determine the level of detail that should be applied to the analysis of the hazards at later stages.

7.3.6.5 Assumptions

It is common for a QRA to involve a number of assumptions. These may relate to aspects of the design (particularly when a project is at an early stage), data sources used or parameter values that are adopted for modelling. Assumptions are typically documented in an Assumption Register.

7.3.6.6 Scenario Definition

Upon determination of the hazards to be included and the level of detail that should be applied, it is then necessary to develop these into modelling scenarios. This involves describing the scenario in sufficient detail to proceed with the modelling.

The scenario definition step adds further detail including:

- The process conditions (temperature, pressure) within the pipe;
- The composition of the hazardous material;

- The size(s) of the leak that may occur;
- The location(s) at which the leak might occur;
- The volume available to feed the leak; and,
- The likely duration of the leak, given the volume of gas and any action that might be possible to isolate the leak.

It is also common practise to group similar hazards together for the purposes of the subsequent analysis. Using the example above, the hazard identification study may identify a number of ways in which a leak of gas from a pipe could result (such as internal corrosion, external corrosion, fatigue, etc.). All of those could be grouped together into a single 'pipe leak' scenario.

7.3.6.7 Consequence Analysis

The purpose of consequence analysis is to determine the potential outcome(s) of the various scenarios. Consequence analysis may be broken down into the following steps:

- Source term modelling;
- Physical effects modelling; and,
- Impact modelling.

Depending on the tools used by the analyst to perform the QRA, these steps may be performed using separate models, or in a single model that automatically proceeds from one step to the next.

Source Term Modelling
Source term modelling determines the behaviour of the material upon leakage, in terms of:

- Release rate and/or quantity;
- The velocity of the material;
- The phase of the material (liquid, gas/vapour or two-phase); and,
- The conditions within the material upon release (temperature, density, etc.).

Where the material forms a pool of liquid, it will also be necessary to model the pool spreading and rate of vaporisation of material from the pool.

Physical Effects Modelling
Modelling of physical effects predicts the behaviour of the material once it has been released, using the source term modelling results as inputs. The types of physical effects considered may include:

- Gas or vapour dispersion;
- Fire dimensions and heat output (for ignited releases of flammable material); and,
- Size and strength of explosions (for ignited flammable clouds in congested/confined regions).

Since some of the calculations performed can be quite complex, and the number of calculations required in a QRA study can be large, software packages are usually employed to perform the modelling.

Impact Modelling

Impact modelling determines the impact that the various physical phenomena have upon receptors of interest (i.e., people, environmental features or assets, depending on the objectives of the study). For people, the relationship between exposure to a potentially harmful agent (such as toxic gas, thermal radiation or blast overpressure) and the probability of fatality is often expressed using a probit equation. Probit relationships take the form:

$$Pr = A + B \ln C^N t$$

Where Pr is a probit, used to obtain the probability of death. A, B and N are the probit equation constants, C is a concentration in mg/m^3, and t is a duration of exposure in minutes. Values of A, B and N for carbon dioxide are shown in the Assumption 18 of Assumption Register attached in Error! Reference source not found..

Probit values are available in standard tables and are incorporated into the RISKCURVES software.

7.3.6.8 Frequency Analysis

In general terms, frequency analysis is used to calculate:

- The likelihood of a given release of dangerous material occurring – this is usually expressed as a frequency (e.g. 1×10^{-3} per year, or once in a thousand years);
- Given that a release has occurred, the probability that a given type of physical effect follows. For example, for releases of flammable material, the type of effect may depend on whether the material is ignited soon after the release begins, or at some time later; and,
- Given that a certain type of physical effects results, the probability of an undesired outcome. This may depend on the wind direction, the probability that a person is present within the hazard range, and the probability of successful emergency action.

Frequency analyses generally falls into three categories:

- Use of relevant historical data;
- Use of analytical or simulation techniques (such as fault tree analysis or event tree analysis); and,
- Use of expert judgment.

Historical data may relate to the frequency of releases of varying sizes from different types of equipment (e.g., the frequency of small leaks from flanges), or to the frequency of accidents on facilities of interest (e.g. the frequency of spills during transfer of cargoes of dangerous substances from ships).

7.3.6.9 Risk Analysis

In simple terms, risk is the chance of an undesired outcome. The chance is usually expressed as a frequency; the undesired outcome may be fatality, environmental damage or financial loss. For this study, the focus is on the risk to people:

- Individual risk, usually expressed as the risk of harming a hypothetical person with a defined set of characteristics. Individual risk results may be expressed as a point value (the individual risk to a hypothetical person at a given geographical location), as a graph of individual risk versus distance (a risk transect) or as contours overlaid on a map.

7.3.6.10 Risk Assessment and Risk Reduction

Once the risk analysis results have been obtained, it is necessary to assess their significance. This often involves comparison of the results against pre-defined criteria. Risk criteria may be established by regulators or set internally by the company. Risk criteria usually define:

- The level of risk which is deemed unacceptable (except perhaps in extraordinary circumstances); and,
- The level of risk which is considered so low that further efforts to reduce the risk are unnecessary.

Between these two levels is a region in which the risk may be considered tolerable, on the condition that all appropriate measures have been taken to control the risk.

The risk analysis results may indicate a need to consider the implementation of further measures to reduce the risk. The analysis outputs may then be interrogated to determine whether there are any particular scenarios which dominate the risk profile. Where such key risk contributors can be identified, it is prudent to focus efforts to reduce the risk on these scenarios.

Once potential risk reduction measures have been postulated, their effectiveness may be evaluated by modifying the analysis inputs to include them and re-running the calculations. The final decision about whether to implement a given risk reduction option depends on:

- The magnitude of the initial risk – if the risk is high relative to the relevant criteria, this will provide a stronger driver for taking action;
- The size of the risk reduction that would be achieved if the measure were to be introduced; and,
- The cost of implementing the measure.

It should be noted that consideration of the costs and benefits of implementing a risk reduction measure is usually weighted in favour of safety, such that the costs have to be much greater than the benefits before a measure can be ruled out.

7.3.7 Risk Acceptance Criteria

The individual risk is calculated in the QRA study. For the purposes of assessing the QRA results in this study, UK HSE's risk criteria have been adopted. The UK Health and Safety Executive (HSE) has published general risk criteria [3] applicable to major industrial hazards and these criteria are presented in below.

The UK HSE divide levels of individual risk into three bands, as illustrated in Figure 7.1.

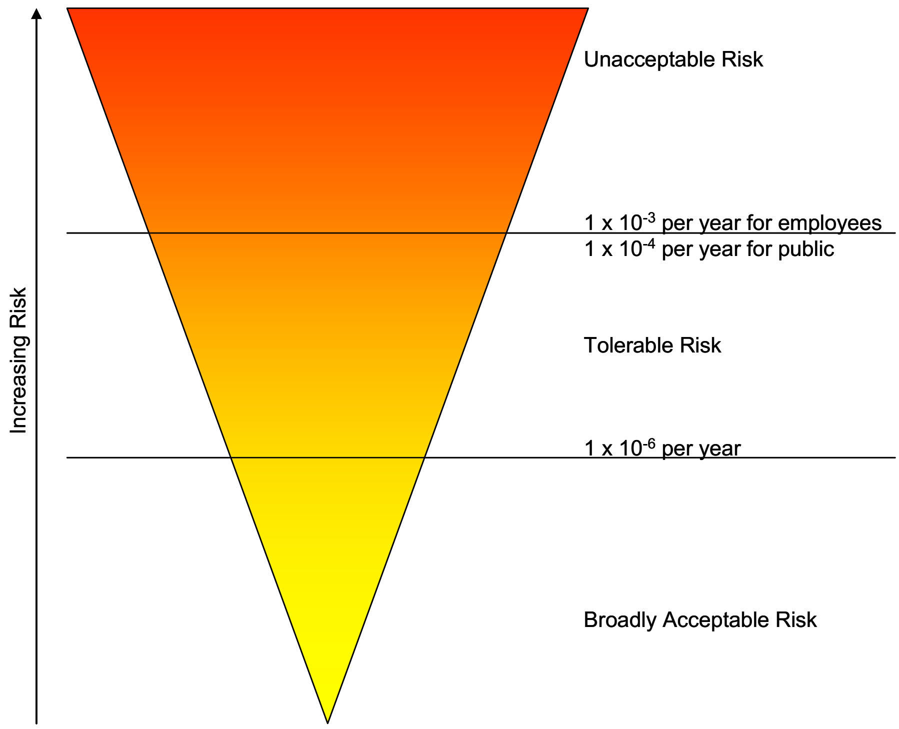


Figure 7.1 – UK HSE tolerability of risk

Risks that are within the highest band are considered unacceptable. Where this is the case, action should be taken to reduce the risk, or the activity giving rise to the risk should be stopped. Conversely, risks falling within the lowest band are 'broadly acceptable'. Such risks are considered to be insignificant and adequately controlled.

Where an individual fatality is assessed to occur with a frequency of 1×10^{-3}/yr or greater, this is considered to be unacceptable or intolerable and risk reduction measures are required to reduce the risk to "Tolerable" or "ALARP". Where an individual fatality is assessed to occur with a frequency of 1×10^{-6}/yr or less, this is considered to be "Broadly Acceptable", with no further consideration of risk reduction measures necessary.

Between the "Broadly Acceptable" and "Unacceptable" regions, there is a region in which the risk is considered tolerable as long as it is 'as low as reasonably practicable. In ALARP region, risk reduction measures are provided when the cost of any further risk reduction measures would be grossly disproportionate (i.e., much greater than) to the benefits gained.

The HSE individual risk boundaries are summarised in Table 7.12. It should be noted that the HSE criteria are stated as Individual Risk per Annum (IRPA) and take into account the time for which an individual may be present at a given location, together with other factors such as whether the individual is located indoors or outdoors.

For the purpose of this coarse QRA, the focus is on the offsite risk to personnel and hence the risk criteria to be adopted would be 1×10^{-4} per year.

Table 7.12 – UK HSE individual risk criteria

Risk Level	Individual Risk to Public
Unacceptable	Greater than $1x\ 10^{-4}$ per year
Tolerable	Between 1×10^{-4} and 1×10^{-6} per year
Broadly acceptable	No greater than 1×10^{-6} per year

7.3.8 Scenario Definition

7.3.8.1 Hazard Identification

Upon review of HAZID study completed for the LCO_2 offloading concepts and concept PFD and design envelopes for offloading scenarios provided in **Error! Reference source not found.** and based on LR's experience with QRAs, the following scenarios were included in the QRA study:

- Loss of containment from offloading manifold and pipelines
- Loss of containment from vapour return line
- Loss of containment from tank caused by ship collision
- Loss of containment from offloading lines to the terminal storage tanks
- Loss of containment from send-out line to the third party users (up till the battery limit of the LCO_2 offloading concept)

7.3.8.2 Representative LCO_2 Offloading Concept

Given that there are similarities between the various LCO_2 offloading concepts, concept 3 was selected to be representative of concept 1 and 2 as it is the most complex out of the three concepts, involving both aspects of ship-to-ship and ship-to-shore offloading. Concept 3 will also allow the QRA to cover two distinct locations of interest (1 – anchorage and 2 – terminal). As for reasons of exclusion of concept 4, refer to the assumption 03 of the assumption register attached in **Error! Reference source not found.**.

7.3.8.3 QRA Scenarios

The first step in definition of scenario is to sub-divide the offloading system into isolatable sections. Isolatable sections are a group of connected equipment items (pipes, vessels, etc.) containing process materials at similar conditions of temperature, pressure and composition. Isolatable section boundaries may also be defined by isolation points (such as emergency shut-off valves).

A summary of the isolatable sections selected for the QRA are presented in Table 7.13 and the sections mark-up is shown Assumption 06 of Assumption Register attached in **Error! Reference source not found.**.

Table 7.13 – QRA scenarios

Concept	Scn No.	Location	Description	Phase	Pressure (bara) Note 1	Temp. (°C) Note 1	Density (kg/m³)	Line/Equip-ment for Inventory	Size (")	Length (m)	Static Volume (m³)	Static Mass (kg)	Neighbouring Section / Inventory when Isolation Fails
3	1	Anchorage	Merchant vessel LCO_2 discharge header ESDV to offloading station ESDV	L	15	-30	1075.8	LCO_2 discharge line	6	100	2.7	2,852	85% volume of merchant vessel LCO_2 storage tank (1,700 m³) Note 2
3	2	Anchorage	LCO_2 offloading arm between merchant vessel and LCO_2 receiving vessel	L	15	-30	1075.8	Manifold	6	10	0.8	855	1
								Loading arm	6	20			
3	3	Anchorage	LCO_2 inlet to LCO_2 receiving vessel storage tank inlet ESDV	L	15	-30	1075.8	LCO_2 inlet line	6	80	2.1	2,281	2

Concept	Scn No.	Location	Description	Phase	Pressure (bara) Note 1	Temp. (°C) Note 1	Density (kg/m^3)	Line/Equip-ment for Inventory	Size (“)	Length (m)	Static Volume (m^3)	Static Mass (kg)	Neighbouring Section / Inventory when Isolation Fails
3	4	Anchorage	LCO_2 receiving vessel vapour header ESDV to loading arm	V	15	-20	35.95	Vapour return line	4	100	1.2	42	15% volume of receiving vessel LCO_2 storage tank (1,500 m^3) Note 3
3	5	Anchorage	Vapour loading arm between merchant vessel and LCO_2 receiving vessel	V	15	-20	35.95	Manifold	4	10	0.4	13	6
								Loading arm	4	20			
3	6	Anchorage	Merchant vessel offloading station vapour line ESDV to merchant vessel LCO_2 storage tank	V	15	-20	35.95	Vapour return line	4	80	300.9	10,785	5
								15% volume of merchant vessel LCO_2	-	-			

Concept	Scn No.	Location	Description	Phase	Pressure (bara) Note 1	Temp. (°C) Note 1	Density (kg/m^3)	Line/Equip-ment for Inventory	Size (“)	Length (m)	Static Volume (m^3)	Static Mass (kg)	Neighbouring Section / Inventory when Isolation Fails
								storage tank (300 m^3) Note 2					
3	7	Terminal	LCO_2 receiving vessel discharge header to LCO_2 receiving vessel offloading station ESDV	L	15	-30	1075.8	LCO_2 discharge line	16	100	18.8	20,278	8
3	8	Terminal	LCO_2 offloading arm between LCO_2 receiving vessel and bulk liquid terminal	L	15	-30	1075.8	Manifold	16	10	5.7	6,132	9
								Loading arm	16	20			
3	9	Terminal	LCO_2 offloading into the liquid bulk terminal	L	7	-50	1075.8	LCO_2 supply lines	16	1,000	34,188.5	36,779,988	10
								85% volume of terminal	-	-			

Concept	Scn No.	Location	Description	Phase	Pressure (bara) Note 1	Temp. (°C) Note 1	Density (kg/m³)	Line/Equip-ment for Inventory	Size (")	Length (m)	Static Volume (m³)	Static Mass (kg)	Neighbouring Section / Inventory when Isolation Fails
			storage tanks					storage tanks (17,000 m³ for each tank) Note 4					
3	10	Terminal	LCO_2 send-out to 3rd party users	L	7	-50	1075.8	Send-out lines	16	100	18.8	20,278	9
3	11	Anchorage	Tank leakage due to ship collision at anchorage (LCO_2 receiving vessel)	L	15	-30	1075.8	Receiving vessel LCO_2 storage tank	-	-	10,000	10,758,000	Not applicable Note 5

Note 1: Heat & Material Balances (HMB) is not available for the project at this conceptual stage. Operating conditions (i.e., pressure and temperature) are assumed to be maintained at the storage conditions for the purpose of the coarse QRA. These assumptions and scenarios need to be revisited when the project enters the next phase with actual design in place.

Note 2: Volume of the merchant ship storage tank is assumed to be 2,000m³.

Note 3: Volume of the LCO_2 receiving vessel storage tank is assumed to be 10,000m³.

Note 4: Volume of bulk liquid terminal storage tank is assumed to be 20,000m³.

Note 5: ESD isolation success/fail is not applicable to this scenario. The release continues up to the maximum release duration, 1,200 seconds.

7.3.9 Consequence Analysis

The consequence analysis has been performed using RISKCURVES software, version 12. RISKCURVES is internationally recognised as one of the 'industry standard' packages for this purpose. The programme automatically performs all of the required source term, physical effects and impact modelling calculations for each scenario defined by the user.

7.3.9.1 Release Rate Outcome

The calculated release rate results are presented in Table 7.14.

Table 7.14 – Release rates

Scenario No.	Location	Description	Initial Release Rate (kg/s)			
			5mm	25mm	100mm	FBR
001	Anchorage	Merchant vessel LCO_2 discharge header ESDV to offloading station ESDV	0.67	16.71	94.44 1)	94.44 1)
002	Anchorage	LCO_2 offloading arm between merchant vessel and LCO_2 receiving vessel	0.67	16.71	94.44 1)	94.44 1)
003	Anchorage	LCO_2 inlet to LCO_2 receiving vessel storage tank inlet ESDV	0.67	16.71	94.44 1)	94.44 1)
004	Anchorage	LCO_2 receiving vessel vapour header ESDV to loading arm	0.06	1.5	23.95	23.95
005	Anchorage	Vapour loading arm between merchant vessel and LCO_2 receiving vessel	0.06	1.5	23.95	23.95
006	Anchorage	Merchant vessel offloading station vapour line ESDV to merchant vessel LCO_2 storage tank	0.06	1.5	23.95	23.95
007	Terminal	LCO_2 receiving vessel discharge header to LCO_2 receiving vessel offloading station ESDV	0.67	16.71	267.61	354.86 1)
008	Terminal	LCO_2 offloading arm between LCO_2 receiving vessel and bulk liquid terminal	0.67	16.71	267.61	354.86 1)
009	Terminal	LCO_2 offloading into the liquid bulk terminal storage tanks	0.49	12.35	197.56	354.86 1)
010	Terminal	LCO_2 send-out to third party users	0.49	12.35	181.99	354.86 1)
011	Anchorage /Terminal	Tank leakage due to ship collision at anchorage (LCO_2 receiving vessel)	39749 2)			

1) The maximum release rate for the flows driven by pump or compressor are limited by 125% of the discharge flow as documented in Assumption 11 of Assumption Register attached in **Error! Reference source not found.**.
2) The release diameter of 1,200mm have been adopted for tank leakage modelling due to ship collision as documented in Assumption 06 of Assumption Register attached in **Error! Reference source not found.**.

7.3.9.2 Toxic Gas Dispersion

The toxic gas dispersion results for risk calculation are presented in Table 7.15.

Table 7.15 – Toxic gas dispersion results

Location	Scenario No.	Isolated / Un-isolated	Hole Size (mm)	Distance to 1% Lethality (m)		
				1.5F	5D	9D
Anchorage	001	Isolated	5	5	5	5
			25	22	21	20
			100	77	61	57
			FBR	77	61	57
Anchorage	001	Unisolated	5	5	5	5
			25	22	22	21
			100	77	61	57
			FBR	77	61	57
Anchorage	002	Isolated	5	5	5	5
			25	22	21	20
			100	64	60	57
			FBR	64	60	57
Anchorage	002	Unisolated	5	5	5	5
			25	22	21	20
			100	77	61	57
			FBR	77	61	57
Anchorage	003	Isolated	5	5	5	5
			25	22	21	20
			100	77	61	57
			FBR	77	61	57
Anchorage	003	Unisolated	5	5	5	5
			25	22	21	20
			100	77	61	57
			FBR	77	61	57
Anchorage	004	Isolated	5	-	1	1
			25	2	2	2
			100	12	17	21
			FBR	12	17	21
Anchorage	004	Unisolated	5	-	1	1
			25	2	2	2
			100	46	35	31
			FBR	46	35	31
Anchorage	005	Isolated	5	-	1	1
			25	1	2	2
			100	10	13	17
			FBR	10	13	17
Anchorage	005	Unisolated	5	-	1	1
			25	1	2	2
			100	46	35	31
			FBR	46	35	31
Anchorage	006	Isolated	5	-	1	1
			25	2	2	2

Location	Scenario No.	Isolated / Un-isolated	Hole Size (mm)	Distance to 1% Lethality (m)		
				1.5F	5D	9D
			100	40	35	31
			FBR	40	35	31
Anchorage	006	Unisolated	5	-	1	1
			25	2	2	2
			100	46	35	31
			FBR	46	35	31
Terminal	007	Isolated	5	5	5	5
			25	22	21	21
			100	135	111	102
			FBR	160	131	119
Terminal	007	Unisolated	5	5	5	5
			25	22	21	20
			100	152	111	102
			FBR	183	130	119
Terminal	008	Isolated	5	5	5	5
			25	22	21	21
			100	123	111	102
			FBR	130	122	119
Terminal	008	Unisolated	5	5	5	5
			25	24	22	22
			100	154	114	102
			FBR	171	125	116
Terminal	009	Isolated	5	6	6	6
			25	15	17	17
			100	115	109	96
			FBR	144	142	132
Terminal	009	Unisolated	5	6	6	6
			25	15	17	17
			100	161	109	96
			FBR	236	150	132
Terminal	010	Isolated	5	5	6	6
			25	13	15	15
			100	112	106	94
			FBR	141	143	133
Terminal	010	Unisolated	5	6	6	6
			25	16	18	18
			100	163	112	99
			FBR	227	147	131
Anchorage	011 [1)]	N/A	1200	2,023	2,311	2,632
Terminal	011 [1)]	N/A	1200	1,571	1,539	1,520

1) These results are based on the assumption that 70% of the CO_2 will vaporize upon a 1,200mm release hole size. Refer to Assumption 06 of the Assumption Register.

7.3.10 Frequency Analysis

The frequency of releases from equipment has been determined by estimating a parts count, which is based on reference to the vessel P&IDs of various projects that LR had been involved in. The parts count for the QRA scenarios are presented in the Assumption 13 of Assumptions Register attached in **Error! Reference source not found.**. The generic frequency data used in this QRA is documented in the Assumption 14 of Assumption Register attached in **Error! Reference source not found.**.

7.3.10.1 Initiating Release Frequency

The counted number of parts is multiplied by this frequency data to tabulate a frequency of release by hole size for each QRA scenarios. Also, the annual utilisation for each operation in Assumption 04 of Assumption Register attached in **Error! Reference source not found.** is taken into account during the release frequency estimation.

The estimated release frequency is summarized in Table 7.16.

Table 7.16 – Initiating release frequency

Scenario No.	Isolated / Un-isolated	Initiating Release Frequency (/yr)			
		5mm	25mm	100mm	FBR
001	Isolated	8.39E-04	2.72E-04	7.21E-05	1.31E-04
	Un-isolated	1.71E-05	5.56E-06	1.47E-06	2.67E-06
002	Isolated	1.51E-03	1.32E-04	3.87E-06	5.48E-05
	Un-isolated	3.08E-05	2.70E-06	7.89E-08	1.12E-06
003	Isolated	2.37E-04	8.56E-05	1.01E-05	1.96E-05
	Un-isolated	4.84E-06	1.75E-06	2.06E-07	4.00E-07
004	Isolated	1.24E-03	2.17E-04	3.88E-05	4.05E-05
	Un-isolated	2.54E-05	4.43E-06	7.93E-07	8.27E-07
005	Isolated	1.32E-03	1.08E-04	3.36E-06	4.70E-05
	Un-isolated	2.69E-05	2.20E-06	6.86E-08	9.59E-07
006	Isolated	3.48E-04	1.31E-04	3.82E-05	6.12E-05
	Un-isolated	7.10E-06	2.67E-06	7.80E-07	1.25E-06
007	Isolated	8.31E-05	3.84E-05	8.98E-06	1.50E-05
	Un-isolated	1.70E-06	7.83E-07	1.83E-07	3.05E-07
008	Isolated	3.77E-04	3.62E-05	2.27E-06	1.58E-05
	Un-isolated	7.69E-06	7.39E-07	4.63E-08	3.23E-07
009	Isolated	6.30E-05	2.38E-04	7.37E-05	9.99E-05
	Un-isolated	1.29E-06	4.86E-06	1.50E-06	2.04E-06
010	Isolated	1.34E-04	5.94E-05	1.71E-05	2.82E-05
	Un-isolated	2.74E-06	1.21E-06	3.50E-07	5.76E-07
011-A [1)]	N/A	9.50E-08			
011-T [1)]	N/A	2.37E-08			

1) 013-A: Anchorage, 013-T: Terminal

7.3.10.2 Event Tree Analysis

The hazardous event outcome frequencies are derived from the initiating release frequency and condition probabilities.

Event tree analysis (ETA) is an inductive logic and probabilistic tool used to quantitatively estimate the distribution of event outcomes following an initiating event (e.g. leak scenario). An event tree starts with an initiating event and progresses through a series of successes or failures of intermediate events called pivotal events, until an end event is reached. A sample ETA is presented in the Assumption 16 and the relevant event tree probabilities are presented in Assumption 17 of Assumption Register attached in Error! Reference source not found..

7.3.11 Risk Results

The individual risk contours illustrate the levels of individual risk to a hypothetical person who is present all of the time (24 hours a day, 365 days a year) at a given location. This LSIR contour expresses the risk exposure to any individual, if initially present in a particular area for one whole year or for the full duration of the activity. The risk exposure is calculated for all relevant leak hazards and summed to give the overall risk in particular areas. In the fatality estimation, the consequences of each outcome from an accidental event are represented by the probability of death for an individual initially present in a particular area when the event occurs.

Table 7.17 summarises the representative concept selected to be assessed in the coarse QRA.

Table 7.17 – Cases for Risk Assessment

Concept	Description	Location Note 1	Time Percentage Note 2	Transfer Rate
3	Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel	Anchorage	19%	StStransfer: 272 t/h
		Terminal	4.70%	Ship-to-shore transfer: 1,022 t/h

1) The location set for modelling is presented in assumption 03 of the assumptions register
2) There are different offloading frequencies expected at the anchorage and terminal. Refer to assumption 04 of the assumptions register for the frequency of LCO_2 offloading.

7.3.11.1 Risk Contours at Anchorage

The risk contour for concept 3 which involves the initial LCO_2 offloading operation from the merchant vessel to the LCO_2 receiving vessel at anchorage is shown in Figure 7.2.

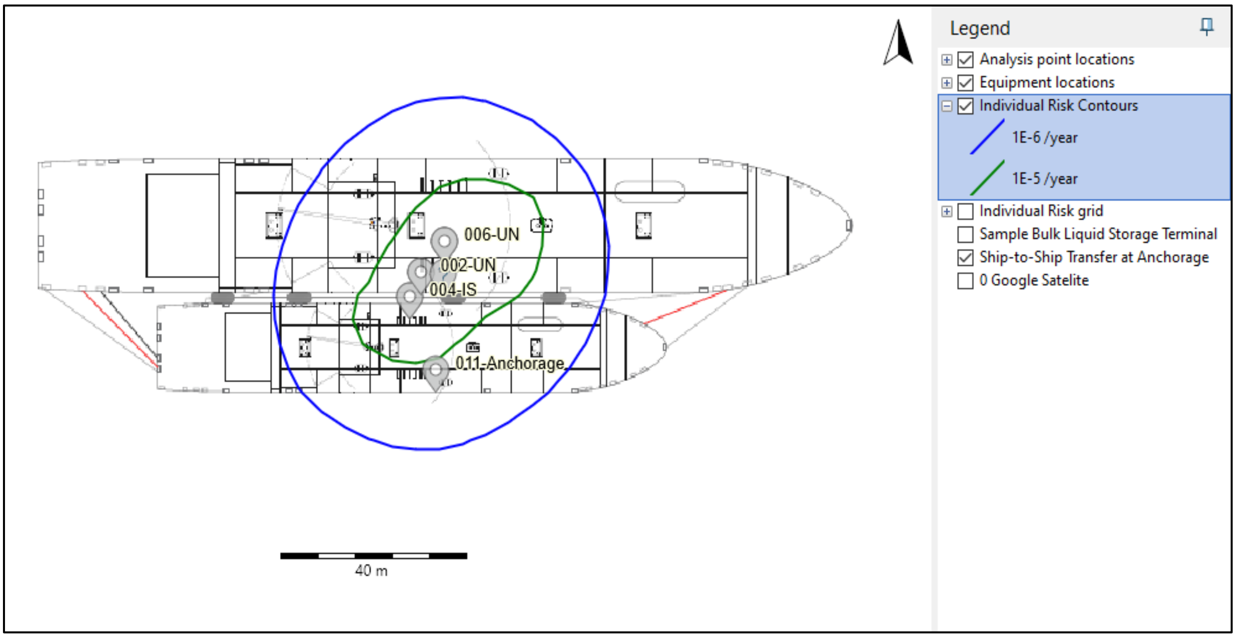


Figure 7.2 – LSIR contours – Concept 3 – LCO_2 offloading between merchant ship and LCO_2 receiving vessel at anchorage (assuming 70% vaporisation on ship collision scenario)

For the purpose of the study, a hypothetical location was selected at one of the anchorages at Port of Rotterdam (POR) to allow for visualisation of the risk contours and the extent of the risk levels arising from the proposed LCO_2 offloading operation between the merchant ship and LCO_2 receiving vessel. The risk contour shows the risk to personnel in the vicinity such as crew onboard either vessels or other nearby vessels in the anchorage. For this offloading concept, the risk criteria is met as there is no 1×10^{-4}/yr LSIR contour generated.

7.3.11.2 Risk Contours at Bulk Storage Liquid Terminal

The risk contour for concept 3 which involves the subsequent LCO_2 offloading operation from the LCO_2 receiving vessel to the bulk liquid storage terminal is shown in Figure 7.3.

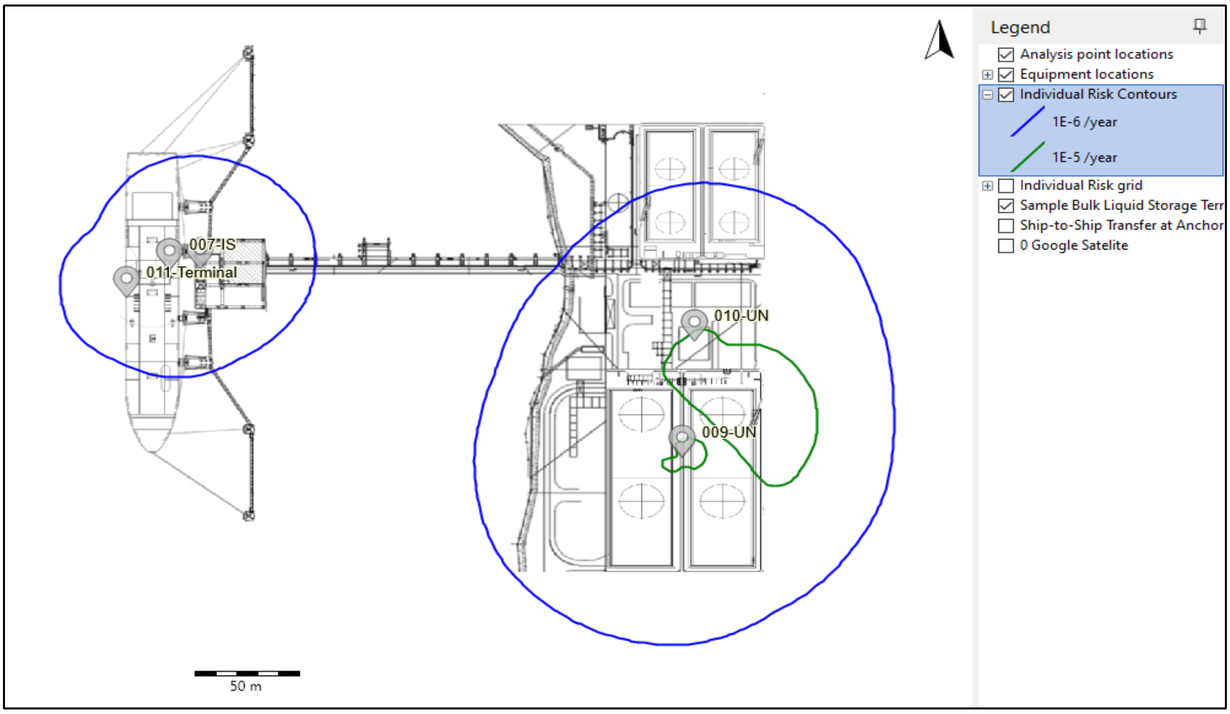


Figure 7.3 – LSIR contours – Concept 3 – LCO_2 offloading between LCO_2 receiving vessel and bulk liquid storage terminal (assuming 70% vaporisation on ship collision scenario)

For the purpose of the study, a hypothetical onshore location was selected in Rotterdam to allow for visualisation of the risk contours and the extent of the risk levels arising from the proposed offloading concept. The risk contour was produced for the LCO_2 offloading operation between the LCO_2 receiving vessel and the bulk liquid storage terminal (up till the battery limits of the offloading concept which includes the onshore storage tanks) which shows the risk to personnel in the vicinity such as crew onboard the vessel and surrounding facilities around the terminal. For this offloading concept, the risk criteria is met as there is no 1 x 10^{-4}/yr LSIR contour generated.

7.3.12 Sensitivity Study

A sensitivity study was carried out to assess for changes in the risk results assuming the worst-case scenario where 100% of the LCO_2 is vaporised upon a ship collision scenario (Scenario 011) instead of the initial assumption of 70% being vaporised (refer to Assumption 06). While there is an increase in consequence distances (approximately 200 m increase for all wind conditions), the risk contours remain unchanged from those shown in Section 7.3.11 as the frequency remains unchanged (relative low in the magnitudes of 1 x 10^{-8}/yr). Furthermore, it shall be noted this sensitivity case (assuming 100% LCO_2 vaporised) is conservative as LCO_2 is expected to exist as a solid/gaseous phase upon release to ambient conditions, whereby some amount of gaseous CO_2 may have been dissolved in water and lesser gaseous CO_2 will be released if CO_2 is in the solid phase.

7.4 References

[1] British Standards Publication, BS ISO 31000: 2018, Risk Management – Principles and Guidelines, BSI, 2018

[2] British Standards Publication, BS ISO 31010: 2019, Risk Management – Risk Assessment Techniques, BSI, 2019

[3] Reducing risks, protecting people – HSE's decision-making process, Health and Safety Executive, 2001

8. Operating Personnel Competency Standards

8.1 Overview

As the shipping industry faces the ongoing challenge to reduce CO_2 emissions to the earth's atmosphere, solutions are being sought by the marine industry. Amongst these is exploring the potential for safe and efficient carbon capture and storage onboard ships followed by a means for transfer for storage ashore. To be successful not only is it necessary to define the engineering and technology requirements but the role of humans with these systems must be explored. As a result, the aim of this part of the study was to focus on the human interface and define operating personnel's competency standards as they would relate to taking CO_2 captured and stored onboard a ship and transferring it for eventual storage ashore.

The results of this work were the creation of two competency frameworks. The first framework, "Proposed Competencies for Handling Captured Liquid CO_2 Onboard ships", provides proposed competencies for handling captured LCO_2 onboard ships. This relies on the existing STCW requirements for minimum standards of competence in training for ships subject to the IGF Code as a starting point. These requirements were examined within the context of operational, safety and environmental tasks that seafarers would undertake to successfully handle, store and transfer liquid CO_2 either to another vessel or ashore. The results were documented in two tables: first, specification of minimum standards of competence in basic training and a second table for advanced training. These tables were organized in the standardised STCW format by using tables and first documenting a relevant competency and then specifying the following information for each:

- Knowledge, understanding and proficiency.
- Methods for demonstrating competence.
- Criteria for evaluating.

A second framework, "LCO_2 Handling Competency Information – Shipboard and Shoreside Personnel", has been created as a supplement to proposed seafarer's STCW requirements to provide further details with regards to competencies related to shipboard management, operational and support personnel's tasks as well as the competencies required for shoreside personnel who would interface with and support LCO_2 unloading / loading, transfer and storage operations. This shoreside support extended to personnel within the marine / shipping company, the terminal, the port and other involved entities.

To be more specific, the second framework highlights competencies by job function / role. Given the complexity of the operations and the various personnel that will contribute their efforts to various operational sequences, a matrix was created to specify who would be expected to hold particular competencies associated with various topics or operations. The major topics or operations for LCO_2 handling were divided into the following:

1. Hazards
2. Overall safety / risk management
3. Operational / process safety
4. Occupational safety
5. Regulations, local requirements, industry guidelines
6. Emergency response

7. Pre-planning
8. Offloading systems / equipment operations
9. Connect / disconnect operations
10. Offloading operations
11. SIMOPS
12. ISO tank container
13. Maintenance

For each of these topics or operations, the competencies required by personnel category / job function were specified. The categories of personnel were as follows:

- Shipboard personnel
    - Management level (senior officers)
    - Operational level (junior officers)
    - Support (ratings)
- Shoreside
    - Marine Company (support) personnel
    - PIC
    - Terminal management, supervisors and operators / workers
    - Port personnel / authorities
    - Support functions from other companies including crane operators, tug operators and emergency responders.

These two frameworks and their associated details lay out the additional competency requirements that should be considered to supplement current shipboard, terminal, and port operations such that LCO_2 can be successfully handled and stored for later treatment, use or sequestration.

8.2 Proposed Competencies for Handling Captured Liquid CO_2 Onboard Ships

Competencies for handling captured Liquid CO_2 onboard ships have been derived using the framework indicated in STCW Section A-V/3 relating to IGF Code and as per STCW Chapter V for Tankers and for Liquefied Gas Tankers.

Guidelines for the Minimum Requirements for the Training and Qualifications of Masters, Officers and Ratings and other personnel on ships carrying captured Liquid CO_2.

Note – LCO_2 receiving vessel will comply with IGC code and personnel would be certified as per STCW requirements for Liquefied Gas Tankers. Below information is for completeness and for guidance or reference specific to competence for LCO_2 carriage and handling.

Basic Training

Every candidate for certification in basic training for handling captured LCO_2 onboard ships shall:

1.1. have successfully completed the approved basic training as required, in accordance with their capacity, duties and responsibilities as set out in Table 8.1 below; and

1.2. be required to provide evidence that the required standard of competence has been achieved in accordance with the methods and the criteria for evaluating competence tabulated in columns 3 and 4 of Table 8.1; or

1.3. have received appropriate training and certification according to the requirements for service on liquefied gas tankers as set out in STCW regulation V/3, paragraph 6, except for the requirements regarding firefighting and flammable products.

Advanced Training

Every candidate for a certificate in advanced training for handling captured LCO_2 onboard ships shall:

1.1 have successfully completed the approved advanced training as required in accordance with their capacity, duties and responsibilities as set out in Table 8.2; and

1.2 provide evidence that the required standard of competence has been achieved in accordance with the methods and the criteria for evaluating competence tabulated in columns 3 and 4 of Table 8.2 below;

or

1.3 have received appropriate training and certification according to the requirements for service on liquefied gas tankers as set out in STCW regulation V/3, paragraph 9, except for the requirements regarding firefighting and flammable products.

Table 8.1 – Specification of minimum standard of competence of basic training for ships carrying captured liquid CO_2

(Adapted from STCW Code Table A-V/3-1)

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
1.	Contribute to the safe operation of a ship	A. Design and operational characteristics of OCCS and storage of LCO_2 onboard ships 1. Basic knowledge of onboard carbon capture systems and LCO_2 storage, loading / unloading, transfer systems: 1.1 Liquid CO_2 characteristics 1.2 Properties, phases, and characteristics 1.3 LP and MP conditions - pressure and temperature, including vapor pressure/ temperature relationship. 1.4 LCO_2 loading / unloading, transfer and storage systems 1.5 General arrangement of liquid CO_2 storage systems onboard ships 1.6 LCO_2 hazards, safety, security and marine zones and areas 1.7 Typical contingency plan for liquid CO_2 offloading operations 1.8 LCO_2 monitoring, control and safety systems aboard LCO_2 capturing ships and receiving vessels 2. Basic knowledge of liquid CO_2 loading / unloading, transfer and storage systems' operations onboard LCO_2 capturing ships and receiving vessels: 2.1 Piping systems, including rigid and flexible insulated piping and valves	Examination and assessment of evidence obtained from one or more of the following: .1 approved in-service experience on board ships fitted with OCCS or on-board gas carriers carrying LCO_2 .2 approved training ship experience .3 approved simulator training .4 approved training programme	Communications within the area of responsibility are clear and effective. Operations related to ships loading / unloading, transfer and storage of liquid CO_2 are carried out in accordance with accepted principles and procedures to ensure safety of operations

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
		2.2 LP and MP conditions storage including low temperature handling 2.3 Relief systems and protection screens 2.4 Basic loading / unloading, transfer and storage operations and related systems 2.5 Protection against low temperature and precautions against phase change. 2.6 CO_2 leak monitoring and detection 2.7 Equipment related to LCO_2 vapor / boil off gas management including re-condensers, re-liquefication systems, and compressors, as appropriate. 2.8 Equipment related to dehydration operations such as driers. 2.9 Pumps – discharge and booster 2.10 PBU. 2.11 Equipment related to interface with LCO_2 receiving vessels or terminal such as lifting appliances / marine loading arms. 2.12 Measuring equipment such as metering for quantity and CO_2 analyzers for purity. B. Knowledge and understanding of safety requirements and safety management systems onboard ships capturing LCO_2 related to LCO_2 handling and LCO_2 receiving ships		
2.	Take precautions to prevent hazards on a ship carrying captured LCO_2	A. Basic knowledge of the hazards associated with operations on ships carrying captured LCO_2, including:	Examination and assessment of evidence	Correctly identifies, on a SDS, relevant hazards to the ship and to

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
		1. Health hazards including CO_2 Toxicity, asphyxia, and cold burns (frostbite) 2. Environmental hazards of CO_2 3. BLEVE hazards 4. Phase change hazards 5. Inert gas hazards 6. Toxicity hazards 7. Vapor leaks and clouds 8. Extremely low temperatures including causing ductile or brittle fractures in steel. 9. Material incompatibilities for fittings 10. Pressure hazards 11. Quality / quantity differences 12. Impurity impacts / effects on equipment as well as impacts on temperatures, pressures, and compression. 13. Hydrates/ dry ice formation due to free water in CO_2 stream (solubility) 14. Temperature / pressure conditions approaching triple point. 15. Handling of hazardous substances, like NH_3 (for refrigeration system), to support operations. 16. Potential for incompatibility with offloading interfaces of LCO_2 receiving ship or terminal.	obtained from one or more of the following: 1. approved in-service experience on board ships fitted with OCCS or on-board gas carriers carrying LCO_2 2. approved training ship experience 3. approved simulator training 4. approved training programme	personnel, and takes the appropriate actions in accordance with established procedures. Identification and actions on becoming aware of a hazardous situation conform to established procedures in line with best practice.

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
		B. Basic knowledge of hazard controls: 1. Emptying, drying, and monitoring techniques 2. Ventilation 3. Segregation 4. Measures to prevent BLEVE 5. Potential impacts of presence of liquid CO_2 onboard on contingency plans. 7. Boil off gas management. 8. Atmospheric control 9. CO_2 testing and sampling 10. Protection against low temperature damages 11. Understanding of LCO_2 (LP and MP) characteristics on ships as found on SDS		
3.	Apply occupational health and safety precautions and measures	A. Awareness of function of CO_2 measuring instruments and similar equipment: 1. CO_2 & O_2 testing 2. Sampling 3. Gas detection, personal and fixed gas detection, monitoring and alarm systems. B. Knowledge of proper use of specialized safety equipment and protective devices, including:	Examination and assessment of evidence obtained from one or more of the following: 1. Approved in-service experience on board ships fitted with OCCS or on-board gas carriers carrying LCO_2	Procedures and safe working practices designed to safeguard personnel and the ship are observed at all times. Appropriate safety and protective equipment is correctly used. First aid dos and don'ts.

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
		1. Breathing apparatus and evacuating equipment 2. Protective clothing and equipment including potential need for low temperature rated PPE (suits) 3. Resuscitators 4. Rescue and escape equipment 5. Adequate ventilation requirements and monitoring of ventilation, especially in enclosed spaces. C. Basic knowledge of safe working practices and procedures in accordance with legislation and industry guidelines and personal shipboard safety relevant to ships carrying captured LCO_2, including: 1. Precautions to be taken before entering hazardous spaces / enclosed (confined) spaces including those where CO_2 or low oxygen levels may be present. 2. Precautions to be taken before and during repair and maintenance work on liquid / gas CO_2 equipment or systems. 3. Ventilation, exhaust, and monitoring systems for enclosed spaces. 4. Safety measures for cold or hot work. D. Basic knowledge of first aid with reference to SDS.	2. Approved training ship experience 3. Approved simulator training 4. Approved training programme	
4.	Respond to emergencies	A. Basic knowledge of emergency procedures, including emergency shutdown.	Examination and assessment of evidence	The type and impact of the emergency is promptly identified and the response actions

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
		B. Special hazards associated with liquid, gas and solid states of CO_2, associated systems, storage, transfer, and handling on ships carrying captured LCO_2.	obtained from one or more of the following: 1. Approved in-service experience on board ships fitted with OCCS or on-board gas carriers carrying LCO_2 2. Approved training ship experience 3. Approved simulator training 4. Approved training programme	conform to the emergency procedures and contingency plans. Initial actions and follow-up actions on becoming aware of an emergency conform with established practices and procedures. Action taken on identifying muster signals is appropriate to the indicated emergency and complies with established procedures. Clothing and equipment are appropriate. The timing and sequence of individual actions are appropriate to the prevailing circumstances and conditions.

Sl No	Competence	Knowledge, Understanding and Proficiency	Methods for Demonstrating Competence	Criteria for Evaluating
5.	Take precautions to prevent CO_2 release / venting on ships carrying captured LCO_2	Basic knowledge of measures to be taken in the event of leakage/spillage/ venting of CO_2, including the need to: 1. Report relevant information to the responsible persons. 2. Awareness of shipboard spill/leakage/venting response procedures. 3. Awareness of need for communications and coordinated actions with other relevant parties and organizations. 4. Awareness of appropriate personal protection when responding to a release / spill/ leakage of LCO_2..	Examination and assessment of evidence obtained from one or more of the following: 1. Approved in-service experience on board ships fitted with OCCS or on-board gas carriers carrying LCO_2 2. Approved training ship experience 3. Approved simulator training 4. Approved training programme	Procedures designed to safeguard the environment are observed at all times.

8.3 Supplementary Information on Competencies for LCO_2 Handling for Shipboard and Shoreside Personnel

Table 8.3 in this section outlines competencies for various aspects and configurations of liquid carbon dioxide offloading operations. Both shipboard and shoreside personnel competencies are addressed. These competencies are expected to supplement STCW requirements for shipboard personnel and do not replace them.

Competencies are grouped into overall competency topics, and further categorised by topic or operation.

For shipboard personnel, if the competency applies it is marked with an "x" related to the personnel type (management, operational, support). The use of the symbol "-" indicates the competency is not considered applicable.

For shoreside personnel, in the "Other Marine Corporate / Shoreside" column of the competencies table, the title of those who should have a particular competency is listed.

Details about personnel addressed in the competency table

With regards to defining competencies for Liquid LCO_2 Offloading operations, the categories of personnel and levels of responsibility are:

- management level (applies to senior officers). This could be on the offloading ship or LCO_2 receiving vessel. (NOTE: personnel should meet STCW requirements as it applies to the vessel where the officer serves and IGC Code requirements)
- operational level (applies to junior officers). This could be on the offloading ship or LCO_2 receiving vessel. (NOTE: personnel should meet STCW requirements as it applies to the vessel where the officer serves and IGC Code requirements)
- support level (applies to ratings forming part of a navigational or engine watch or other ratings). This could be on the offloading ship or LCO_2 receiving vessel. (NOTE: Should meet applicable STCW and IGC)
- marine corporate or shoreside support:
  - Marine Company personnel related to offloading ship. This could include ship superintendents, technical staff, marine operations, safety & environment department.
  - Marine Company personnel related to LCO_2 receiving vessel. This could include ship superintendents, technical staff, marine operations, safety & environment department.
  - PIC – Person in Charge. The person chosen to oversee the loading / offloading operations and involved in the planning.
  - Company personnel related to terminal (shoreside). This would include Terminal Operator management, supervisors and operators / workers.
  - Port personnel / authorities.
  - Any support functions outside these entities – crane operators, tug operators, emergency responders, etc. (Not addressed in this study)

The following table lists the different functions and levels of responsibility at which the shipboard functions can be carried out. (Informational only)

- Navigation
- Cargo handling and stowage
- Controlling the operation of the ship and care of persons onboard
- Marine engineering
- Maintenance and repair

- Electrical, electronics, and control engineering
- Radio communications

Table 8.2 – Different functions and levels of responsibility (for information)

Function		Level of Responsibility		
		Management	Operational	Support
Deck	Navigation	●	●	●
	Cargo handling and stowage	●		
Deck & Engine	Controlling the operation of a ship and care for persons on board	●	●	
Engine	Marine engineering	●	●	●
	Maintenance & repair	●	●	
	Electrical, electronics and control engineering	●	●	
Radio	Radio communication		●	

Table 8.3 – LCO_2 handling competency matrix – shipboard and shoreside personnel

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
Hazards							
A1	Hazards	Hazards overall	Knowledge of Liquid CO_2 chemical and physical properties and characteristics. This includes understanding of the various phases of CO_2, as well as triple and critical points.	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators, PIC
A2	Hazards	Hazards overall	Knowledge of Liquid CO_2 health hazards including asphyxiation and toxicity, low temperature hazards such as cold burns or exposure to the release of compressed liquid or gas.	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators, PIC
A3	Hazards	Hazards overall	Familiarity with Liquid CO_2 characteristics. This includes health hazards including asphyxiation and toxicity, low temperature hazards such as cold burns or exposure to the release of compressed liquid or gas.	-	-	x	Port Authorities, any Personnel in terminal or support functions.
A4	Hazards	Explosion	Understanding of the potential for explosion (BLEVE).	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators. PIC.
A5	Hazards	Solidification of CO_2	Understanding of the implications of potential plugs / blockages in equipment or lines if pressure and temperature are not maintained within limits.	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators. PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
A6	Hazards	Hazards - Corrosion	Knowledge of factors that can contribute to corrosion including moisture content and impurities.	x	x	-	Marine Corporate shoreside, Terminal management; supervisors, operators.
A7	Hazards	Hazards - Corrosion	Ability to monitor CO_2 content and take appropriate action to reduce conditions and factors that could contribute to corrosion.	x	x	-	Terminal supervisors, operators
A8	Hazards	Hazards - Corrosion	Knowledge of damage mechanisms and their causes including ductile and brittle fracture.	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, PIC.
A9	Hazards	Hazards - failure	Familiarity with the potential failure mechanisms and their causes including ductile and brittle fracture	x	x	-	Terminal supervisors, operators
A10	Hazards	ISO tank container lifting infrastructure	Knowledge of potential hazards associated with CO_2, especially leaks (e.g. from the pressure safety valve) during ISO tank container lifting operations. **Assuming that lifting of ISO tank container / container is not a new operation and the unique aspect is CO_2.	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators, PIC.

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
A11	Hazards	ISO Tank Container	For ISO tank containers, all involved with operations must be knowledgeable about unique hazards related to CO_2.	x	x	-	Marine Corporate shoreside, PIC, Terminal management, supervisors, operators especially involved with lifting
Overall Safety / Risk Management							
B1	Overall Safety / Risk Management	Risk Management	At the planning and management levels, understand need for and process for identifying risks as well as understanding prevention, mitigation and emergency actions.	x	-	-	Marine Corporate shoreside, Terminal Management, PIC.
B2	Overall Safety / Risk Management	Offloading Ops - Plan	During planning, ability to address communications, required procedures and checklists; SIMOPS; sequencing of operations; means for managing changes; emergency response.	x	x	-	Marine Corporate shoreside, Terminal Management, PIC
B3	Overall Safety / Risk Management	Offloading Ops - Plan	Ability to plan and create an LCO_2 offloading plan, taking into account, relevant regulations, port or ship requirements, different involved organizations capabilities and restrictions. The planning must also work across the involved and where necessary, combine, the various parties' safety management systems.	x	-	-	Planning and Management – Marine Corporate Shoreside and Terminal management. PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
B4	Overall Safety / Risk Management	Offloading Ops - Plan	Ability to convey dispersion characteristics, system and equipment capabilities and limitations (including from vent mast) information to those conducting pre-planning and creating the LCO_2 Offloading Plan. NOTE: This will impact determination of safety, security, and marine zones.	x	-	-	Planning and Management – Marine Corporate Shoreside and Terminal management, PIC
B5	Overall Safety / Risk Management	Risk Assessments	For pre-planning, ability to conduct compatibility studies and risk assessments including the recording of required objectives to be met.	x			Marine Corporate shoreside, Terminal Management, PIC.
B6	Overall Safety / Risk Management	Safety management	Ability to determine overall Safety Management approach to be used for offloading including ability to establish agreement on integration of the various safety rules to be followed across the various organizations involved in offloading.	x	-	-	Marine Corporate shoreside, Terminal Management, PIC.
B7	Overall Safety / Risk Management	Controlled Zones	Understanding of the purpose of Safety, Security and Marine Zones is to protect personnel from hazards such as from accidental release during offloading: - high pressure, cold, asphyxiating gas. Also understanding the importance of controlling access to the area from personnel, vehicles, marine traffic, etc.	x	x	-	Marine Corporate shoreside, Terminal Management, PIC. Port Authorities.
B8	Overall Safety / Risk Management	Controlled Zones	Familiarity with the purpose of Safety, Security and Marine Zones and what is needed to comply with rules.	-	-	x	Terminal operators, Support function personnel.

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
B9	Overall Safety / Risk Management	PIC	Knowledge of plan, risks, requirements, procedures / processes and recordkeeping for LCO_2 transfer and offloading.	x	x	-	Marine Corporate shoreside, Terminal Management and supervisors, PIC.
B10	Overall Safety / Risk Management	PIC	Familiarity with overall plan, risks, requirements, procedures / processes and potential recordkeeping for LCO_2 transfer and offloading	-	-	x	Terminal operators, Support function personnel.
B11	Overall Safety / Risk Management	PIC	Ability to effectively work across and communicate with various organizations involved in transfer and offloading. This would extend to being knowledgeable about the various operational phases: • planning, • pre-operational meetings, • preparation for transfer, • pre-operational testing, • connection / disconnection of transfer system (including vapor return), • startup / shutdown, • transfer / offloading, • monitoring and limitations of key indicators throughout operation such as flow and transfer rates and pressure management for each stage of offloading (cool down, full flow, topping up to filling limit); • completion of operation.	x	-	-	Terminal supervisor, PIC.

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
B12	Overall Safety / Risk Management	PIC	Ability to lead the pre-operational review meeting to establish specifics of offloading operation. This would be similar to other offloading / cargo operations but with unique aspects related to managing LCO_2 risks / hazards.	-	-	-	PIC
B13	Overall Safety / Risk Management	PIC and others	Understanding of offloading procedures and related operational parameters. This would extend to familiarity with checklists used for LCO_2 storage, transfer, and offloading operations as well as SIMOPS.	x	x	-	Marine Corporate shoreside, Terminal Management, PIC.
B14	Overall Safety / Risk Management	PIC	Ability to oversee that inventory and functionality tests prior to offloading for all involved, including aspects unique to LCO_2, have been conducted and that monitoring occurs throughout operations. This would extend to CO_2 PPE, communication channels, low temperature protection, gas monitoring, emergency related equipment including ESD testing	x	-	-	PIC
B15	Overall Safety / Risk Management	Oversee and conduct operations	Ability to conduct inventory and functionality tests prior to offloading for all involved, including aspects unique to LCO_2, and conduct monitoring throughout operations. Understanding when and how to report anomalies. This would extend to CO_2 PPE, communication channels, low temperature protection, gas monitoring, emergency related equipment including ESD testing.	x	x	-	Terminal supervisors, PIC
B16	Overall Safety / Risk Management	PIC and others	Knowledge of safety systems including communications systems, emergency release system, emergency shutdowns, QC/DC, CO_2 detection alarms, general alarms, emergency response equipment. For LCO_2, knowledge of the purpose of insulation flanges / sleeves (such as those attached to the receiver) to prevent CO_2 phase changes should be understood.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
B17	Overall Safety / Risk Management	PIC and others	Understanding of functionality of Ship-to-Ship and Ship-to-Shore links to allow tripping of offloading pumps in the event of an emergency shutdown activation.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, PIC
B18	Overall Safety / Risk Management	PIC	Knowledge of safety and security measures for operations such as access to vessel or local area, safety. security or marine zones.	x	x	-	PIC
B19	Overall Safety / Risk Management	Working with PIC	Familiarity with marine aspects of operation including mooring, stability, securing of vessel, influences of weather, meteorological and local conditions. Local conditions to include tides, current, vessel traffic.	x	x	-	PIC
B20	Overall Safety / Risk Management	PIC	Ability to coordinate incident response for safety, security, environmental or emergency events including reporting and documenting incident. Knowledge of incident reporting to include understanding of various organizations to be informed (Implementing Authority and Port Master, for example).	x	-	-	PIC
B21	Overall Safety / Risk Management	Working with PIC	Ability to work with PIC to coordinate incident response for safety, security, environmental or emergency events including reporting and documenting incident. Knowledge of incident reporting to include understanding of various organisations to be informed (Implementing Authority and Port Master, for example).	x	-	-	PIC, Terminal management, supervisor
B22	Overall Safety / Risk Management	PIC	Ability to oversee and terminate, if necessary, any operations including SIMOPS taking place during transfer or offloading operations.	-	-	-	PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
B23	Overall Safety / Risk Management	Working with PIC	Ability to coordinate actions with PIC for various operations including termination, if necessary, of any operations including SIMOPS taking place during transfer or offloading operations.	x	x	-	PIC, Terminal management, supervisor
B24	Overall Safety / Risk Management	Offloading Ops – Risk Assessment	Ability to conduct and modify, as needed, risk assessments for offloading operations. This would include identifying risks and contingencies as well as implement risk controls.	x	-	-	Terminal supervisors, operators, PIC
B25	Overall Safety / Risk Management	Offloading Ops - Plan	Familiarity with LCO_2 offloading plan and relevant checklists to promote safe, environmentally sound operations and effective coordination amongst all partners involved with offloading.	x	x		PIC, Terminal supervisor
B26	Overall Safety / Risk Management	Environment	Familiarity with CO_2 Offloading Management Plan to reduce the potential for release or fugitive emissions.	x	x	-	Terminal supervisor, operator
B27	Overall Safety / Risk Management	Environment	Understanding of environmental impacts of CO_2 including its greenhouse gas potential.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, PIC
Operational / Process Safety							
C1	Operational / Process Safety	Risks associated with various types of operations	Understanding of potential risks associated with LCO_2 operations and the mechanisms for dehydration, compression, liquefaction and vapor / BOG management.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C2	Operational / Process Safety	Risk associated with loss of pressure / vacuum conditions	Understanding of the implications of creating low pressure or vacuum conditions in tanks. Ability to recognize the conditions and take preventative actions.	x	x	-	Terminal supervisor, operator, PIC
C3	Operational / Process Safety	CO_2 Thermodynamic Properties affecting Procedures	Understanding of thermodynamic properties of CO_2 for developing a LCO_2 offloading guideline including: o Temperature / pressure interactions / interrelationships. o Understanding and management of BOG o How to deal with formation of solids / dry ice.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, PIC
C4	Operational / Process Safety	LCO_2 Safety related Properties	Understanding of LCO_2 safety related properties – such as potential for accumulation of CO_2 in low spots, dry ice formation, BLEVE potential.	x	x	x	Terminal Supervisors, operators
C5	Operational / Process Safety	Physical Properties – low temperatures	Understanding how and why low temperatures must be maintained between (-20°C and -54°C) to avoid phase change by: o Providing thermally insulated equipment o Providing materials of construction for storage, transport vessels and piping systems that can withstand required extremes of temperatures and pressures.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C6	Operational / Process Safety	Hazards – temperature and pressure	Understanding the consequences of failing to maintain required temperatures and pressures such as: • Over pressurisation of piping systems • System ruptures creating shrapnel. • High pressure releases causing jet stream of CO_2 to potentially affect people nearby (in the stream with cold burns or since heavier than air, asphyxiation of personnel in the area)	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators. PIC
C7	Operational / Process Safety	CO_2 Properties – temperature and pressure	Understanding of characteristics of CO_2 and the relationship between temperature and pressure to maintain CO_2 in liquid state including: • Impact on densities. • Concept triple point where the three phases of gas, liquid and solid coexist in thermodynamic equilibrium. • Concept of critical point.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators. PIC
C8	Operational / Process Safety	Operations – temperature and pressure	Ability to respond effectively to potential changes of temperature and pressure affecting CO_2 phase changes, including solids formation, during transportation and offloading.	x	x	-	Terminal supervisors, operators
C9	Operational / Process Safety	Safety, security and marine zones	Understanding of the purpose of the various established zones for LCO_2 operations	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C10	Operational / Process Safety	Communications	Ability to report and communicate any changes or issues associated with the zones.	x	x	x	Terminal supervisors, operators, Support function personnel, Port Authority
C11	Operational / Process Safety	Impurities	Understanding the impacts of impurities on: • Temperature – pressure phase equilibria • Vapor pressure affecting storage and offloading • compression power requirements, • corrosion of tanks and pipelines due to formation of carbonic acid from presence of water / moisture.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators, PIC
C12	Operational / Process Safety	Impurities	Ability to conduct regular sampling and analysis to detect / respond to impurities	x	x	-	Terminal supervisors, operators
C13	Operational / Process Safety	Safety	Familiarity with safety components associated with the LCO_2 transfer system including: ESD links; QC/DC and an ERS associated with rigid marine articulating arm systems or fully supported and protected LCO_2 flexible hose systems	x	x	-	Terminal management, supervisors, operators
C14	Operational / Process Safety	Safety	Understanding of LCO_2 BOG Management including pressure and temperature monitoring and control. This would include understanding the role of heat ingress, the impacts related to a warm LCO_2 tank during offloading and how the resulting vapor will need to be managed using compressors, re-condensers and reliquefaction systems (as applicable).	x	x	-	Terminal supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C15	Operational / Process Safety	Temperature Ambient Temperature Impacts	Understanding of the impact of local ambient temperatures on pre-preparation for unloading, unloading operations and completion of unloading operations including: • Implications for heat transfer to CO_2 equipment and the need for insulation and refrigeration capacities. • Maximum and minimum ambient design temperature is critical for components exposed to environmental conditions, such as storage tanks and associated piping. • Influence of local weather • Maximum ambient design temperatures are defined by the IGC Code and Class rules - allowances can be made for particularly hot or cold zones.	x	-	-	Marine Corporate shoreside, Terminal Management, supervisors, operators, PIC
C16	Operational / Process Safety	Process design temperature & pressure	Understanding and knowledge of maximum and minimum temperatures & pressure that equipment and system is designed to safely withstand. It is determined based on anticipated operating conditions, safety factors and potential extreme conditions.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators
C17	Operational / Process Safety	Process operating temperature & pressure	Understanding and knowledge of usual range of temperatures & pressure at which the system or equipment operates under normal conditions.	x	x	-	Marine Corporate shoreside, Terminal Management, supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C18	Operational / Process Safety	Process operating temperature & pressure	Ability to control and maintain temperature & pressure within operating temperature & pressure to preserve phase conditions of CO_2.	x	x	-	Terminal supervisors, operators
C19	Operational / Process Safety	Process operating temperature	Understanding of the importance of insulation, active cooling or heating systems depending on specific application and operating conditions.	x	x	-	Terminal supervisors, operators
C20	Operational / Process Safety	Temperatures and pressures associated with offloading	Understanding of the effect of minimum design temperatures on low temperature properties of materials including 5 % margin and strictly ensure pressure not less than 0.5barg above triple point.	x	x	-	Terminal supervisors, operators
C21	Operational / Process Safety	Temperatures and pressures associated with offloading	Knowledge of the minimum operating temperatures reached during normal operation, start-up, shutdown, or process disruptions, minus 5 °C (margin) of minimum operating temperature.	x	x	-	Terminal supervisors, operators
C22	Operational / Process Safety	Temperatures and pressures associated with offloading	Ability to conduct temperature calculations to at least account for heat transfer between the fluid and vessel.	x	x	-	Terminal supervisors, operators
C23	Operational / Process Safety	Temperatures and pressures associated with offloading	Understanding of minimum design temperatures for depressurization and starting conditions for depressurisation.	x	x	-	Terminal supervisors, operators
C24	Operational / Process Safety	Temperatures and pressures associated with offloading	Understanding of condition needed for start-up of operations such heating and cooldown rates for the system.	x	x	-	Terminal management, supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C25	Operational / Process Safety	Temperatures and pressures associated with offloading	Knowledge of pressure envelopes including minimums and maximum and the interaction of pressure with temperature as well as CO_2 phases (gas, liquid, solid)	x	x	-	Terminal supervisors, operators
C26	Operational / Process Safety	Temperatures and pressures associated with offloading	Understanding of the potential for pressures and temperatures dropping below triple point and rapid expansion with depressurisation.	x	x	-	Terminal supervisors, operators
C27	Operational / Process Safety	Temperatures and pressures associated with interfaces	Understanding of temperature and pressure impacts with interfaces between low pressure systems in supply vessel and medium pressure systems on LCO_2 receiving vessel. This includes LCO_2 and vapor return lines.	x	x	-	Terminal management, supervisors
C28	Operational / Process Safety	Temperatures and pressures associated with offloading	Knowledge of the potential impacts of over pressurisation on PSV activation and on equipment such as pumps, heat exchangers and piping systems (including transfer hoses).	x	x	-	Terminal supervisors, operators
C29	Operational / Process Safety	Offloading Ops – Risk Assessment	Familiarity with risks and risk assessment for offloading operations. Ability to modify operations when required and apply management of change processes to ensure safety / environmental requirements continue to be met.	x	x	-	Terminal supervisors, operators
C30	Operational / Process Safety	Offloading Ops – Risk Assessment	Understanding of how to establish safety zones and monitoring zones based on assessment of offloading risks	x	x	-	Marine Corporate shoreside, Terminal management, supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
C31	Operational / Process Safety	Management of Change	Ability to monitor conditions and identify then manage any changes to conditions. This will require skills for hazard / risk identification and making potential adjustments to operations to maintain acceptable conditions.	x	x	-	Terminal management, supervisors, operators. PIC
Occupational Safety							
D1	Occupational Safety	LCO_2 Safety related Properties	Familiarity with LCO_2 safety properties – such as potential for accumulation of CO_2 in low spots, dry ice, potential for BLEVE, cold burns and how to protect oneself such as PPE requirements	-	-	x	Terminal operators.
D2	Occupational Safety	Safety equipment	Understanding of the proper use of safety equipment such as gas monitoring / sampling / detection equipment.	x	x	-	Terminal supervisors, operators
D3	Occupational Safety	Protective Equipment	Understanding of the various levels (A, B, C) of personal protective equipment suitable for use with CO_2 including which level to use for particular operations.	x	x	-	Terminal supervisors
D4	Occupational Safety	Protective Equipment	Familiarity with donning and doffing of personal protective equipment suitability for use with CO_2 including inspection of equipment for condition prior to use.	-	-	x	Terminal operators
D5	Occupational Safety	Ventilation	Familiarity with the use of ventilation for spaces where CO_2 could be present.	x	x	-	Terminal supervisors.
D6	Occupational Safety	Chemical safety	Familiarity with the use of SDS for CO_2 and any other chemicals associated with LCO_2 operations.	x	x	x	Terminal management, supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
D7	Occupational Safety	ISO Tank Container Operations	Familiarity with LCO_2 hazards and PPE requirements for terminal personnel, including truck drivers. This includes any personnel involved with manually disconnecting / connecting / isolating / securing ISO tank container or related systems / equipment.	-	-	-	Terminal supervisors, operators, Shoreside support
Regulations, local requirements, industry guidelines							
E1	Regulations, local requirements, industry guidelines	Local safety acceptance criteria	Knowledge of any local safety acceptance criteria. At an existing berth, this would include limits related to operation of ship-to-shore equipment (loading arms, gantry cranes). At anchorage, limits would include those related to transfer hoses.	x	-	-	Marine Corporate personnel, Terminal management, supervisors, operators, PIC, Port Authority
E2	Regulations, local requirements, industry guidelines	Industry Guidelines	Familiarity with OCIMF on Mooring Load Analysis During Ship-to-Ship Transfer Operations concerning limiting wave heights for Ship-to-Ship transfer for pairs of vessels.	x	x	-	Marine Corporate personnel, PIC
E3	Regulations, local requirements, industry guidelines	Marine infrastructure – shoreside lifting appliances	For relevant shoreside personnel, knowledge of competencies and training required such as OCIMF Marine Terminal Operator Competence and Training Guide for personnel engaged in operating lifting equipment.	-	-	-	Terminal Management, Supervisor, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
E4	Regulations, local requirements, industry guidelines	Mooring equipment at anchorage including fendering	Familiarity with OCIMF StS Transfer Guide for Petroleum, Chemicals and Liquefied Gases for mooring equipment requirements and understanding of unique CO_2 hazards.	x	x	-	Marine Corporate personnel, Terminal management, supervisors, PIC
E5	Regulations, local requirements, industry guidelines	Preparation of operations	Familiarity with SIGTTO guidance with regards to LNG transfer to guide approach to LCO_2 transfer and preparation for operations. This would include items like having drip trays emptied of any accumulation before operations. This knowledge should be fed into pre-planning and development of Offloading Operations Plan.	-	-	-	Marine Corporate personnel, Terminal management, PIC
E6	Regulations, local requirements, industry guidelines	Safety	Familiarity with design basis such as SIGTTO Recommendations for Emergency Shutdown and Related Safety Systems and the necessary adaptations for LCO_2 offloading operations - This might be relevant for shoreside company personnel like engineers.	x	x	-	Marine Corporate personnel, Terminal management, supervisors, PIC
E7	Regulations, local requirements, industry guidelines	LCO_2 Offloading Procedures Mooring operations	As with standard mooring arrangement, familiarity with existing guidance such as ISO 28640 / 16904 and best practice guidelines such as OCIMF StS Procedures – Planning.	x	-	-	Marine Corporate personnel, Terminal management, supervisors, PIC
E8	Regulations, local requirements, industry guidelines	LCO_2 Offloading Procedures – Completion of filling	Familiarity with reporting requirements, including to Port Authorities, of tank loading conditions and curves.	x	-	-	Terminal management, supervisors, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
E9	Regulations, local requirements, industry guidelines	LCO_2 Offloading Procedures – Finalizing offload and preparation for next operation	Familiarity with documentation requirements related to inspections, maintenance, and repairs.	x	x	-	PIC Terminal supervisors
E10	Regulations, local requirements, industry guidelines	LCO_2 Offloading Procedures – Post offloading review and reporting	Knowledge of documentation requirements, and receiving parties of records, for all aspects of termination of offloading operations. This would include: • Quality / quantity recordkeeping • Incidents or non-compliance during offloading operations – whether related to communications, procedures, or equipment / systems.	x	-	-	Marine Corporate personnel, Terminal management, supervisors, PIC
E11	Regulations, local requirements, industry guidelines	PIC	Understanding of various regulations and requirements. This would include marine as well as on shore requirements depending on the location and interfaces in the offloading operation.	x	x	-	Marine Corporate personnel, Terminal management, supervisors, PIC
Emergency Prevention and Response							
F1	Emergency Prevention and Response	Marine risks	Ability to recognize and respond to marine hazards such as parting of mooring lines including snapback line hazards with due consideration to potential presence of CO_2 in local area.	x	x	-	Terminal management, Supervisors

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
F2	Emergency Prevention and Response	Changes to Emergency Response	Awareness of LCO_2 properties affecting approach to emergency response including firefighting, rescue of personnel, first aid.	x	x	x	Terminal management, Supervisors. Operators. Port Authorities. Shoreside support personnel
F3	Emergency Prevention and Response	Fire fighting	Understanding of potential unique impacts of the presence of LCO_2 during fires including the potential for rapid expansion and oxygen displacement.	x	x	-	Terminal management, Supervisors. Operators. Port Authorities. Shoreside support personnel
F4	Emergency Prevention and Response	Emergency response plans	Familiarity with changes to emergency response plans, including fires, to accommodate presence of CO_2.	x	x	x	Terminal Supervisors, operators
F5	Emergency Prevention and Response	Emergency response plans	Familiarity with changes to emergency response plans for LCO_2 releases to surfaces or to atmosphere. Knowledge of measures to be taken in the event of spillage, leakage, venting.	x	x	x	Terminal Supervisors
F6	Emergency Prevention and Response	Gas Detection	Understanding of CO_2 leak detection system including where to obtain information about location of sensors, alarm and system shutdown setpoints. Also understanding of potential alarm response measures.	x	x	-	Terminal Supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
F7	Emergency Prevention and Response	Safety	Knowledge of impacts of using ESD valves that can be remotely operated. Familiarity with the physical locations of emergency shutdown valves that will be placed at several locations within the LCO_2 transfer system of both the offloading facility and the receiving facility.	x	x	x	Terminal management, Supervisors. Operators. Shoreside support personnel
F8	Emergency Prevention and Response	Safety	Understanding of ESD Systems functions and the difference between two ESD levels, ESD-1 and ESD-2.	x	x	-	Terminal Supervisors, operators
F9	Emergency Prevention and Response	Safety	Understanding of the purpose and function of a single automatic and/or manually activated ERS on each transfer line including the role of the ERC with interlocked isolation valves to minimise the LCO_2 release.	x	-	-	Terminal management, Supervisors
F10	Emergency Prevention and Response	Safety	For manual activation, familiarity with step-by-step manual ERS activation procedures that are posted at the ERS remote (safe) operating location on board the offloading vessel.	x	x	x	n/a

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
F11	Emergency Prevention and Response	LCO_2 Offloading Procedures ESD Testing	Relevant personnel on board vessels and at terminals to have: o ability to conduct functionality tests of ESD systems prior to beginning offloading operations. o Knowledge of equipment / system inspections to be conducted prior to offloading operations. o Understanding reporting requirements to PIC of any anomalies or defects found. o Knowledge of documentation required for pre-operational tests / inspections.	x	x	-	Terminal Supervisors, operators
F12	Emergency Prevention and Response	Water Spray	Knowledge of when and where to use water spray curtain in areas such as the manifold to protect against embrittlement damage. Ability to give due consideration in decision making to the potential for forming carbonic acid.	x	-	-	PIC, Terminal management, supervisors
F13	Emergency Prevention and Response	Special CO_2 requirements	Understand the changes to standard contingency or emergency procedures to accommodate LCO_2, interfaces with other organizations and ability to follow them. This would include communication and reporting requirements including those with Port Authorities.	x	x	-	PIC, Terminal management, supervisors.
F14	Emergency Prevention and Response	Special LCO_2 requirements	Ability to recognize and respond to CO_2 ingress into ship air intakes or machinery spaces after a leak / release. Terminal supervisors and operators would also need to respond to CO_2 ingress if it could be drawn into spaces ashore.	x	x	-	PIC, Terminal supervisors, operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
F15	Emergency Prevention and Response	Special LCO_2 requirements	Based on CO_2 gas dispersion models, understanding of the need to ensure personnel are not located near vent mast if venting is needed thus reducing the potential for personnel exposure.	x	x	-	PIC, Terminal management, supervisors
F16	Emergency Prevention and Response	Special LCO_2 requirements	Familiarity with measures (e.g., restricted zones, safety zones, etc.) to reduce potential personnel exposures in event of venting.	x	x	x	PIC, Terminal management, supervisors, operators, Port Authorities. Shoreside support
F17	Emergency Prevention and Response	Operation termination	Familiarity with criteria for terminating operations including any criteria related to marine, weather, or local environmental conditions.	x	x	-	Terminal management, Supervisors, Operators. Port Authorities, Shoreside support personnel.
F18	Emergency Prevention and Response	CO_2 alarms	Familiarity with CO_2 alarms and actions to take on activation.	x	x	x	Terminal management, Supervisors, Operators. Port Authorities, Shoreside support personnel

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
Pre-planning							
G1	Pre-planning	Roles and responsibilities	Understand the roles and responsibilities of various stakeholders and organizations involved.	x	-	-	Marine Corporate personnel, Terminal management, supervisors, PIC
G2	Pre-planning	Roles and responsibilities	Individuals to understand their roles and responsibilities throughout offloading operations	x	x	x	Marine Corporate personnel, Terminal management, Supervisors, Operators, Port Authorities, Shoreside support personnel
G3	Pre-planning	Vessel Condition – Pre-planning	For pre-planning, understanding of the potential impact of freeboard, draft, loading condition of offloading vessel and the potential impacts related to infrastructure such as reach of marine loading arms and vessel cranes at berth, mooring arrangements (StS or at terminal).	x	-	-	Pre-Planning: Creators of Offloading Plan Marine Corporate personnel, Terminal management, Supervisor, PIC
G4	Pre-planning	Vessel Condition	Familiarity with limits set for vessel factors (freeboard, draft, loading condition) as they relate to offloading infrastructure used during offloading including metocean operational limits	x	x	-	PIC, Shoreside / Terminal operator

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
G5	Pre-planning	Risk Assessment	Understand the need to verify generic risk assessments and mitigation measures, and whether they continue to be valid for specific offloading operations.	x	x	-	Marine Corporate personnel, Terminal management, Supervisor, PIC.
G6	Pre-planning	Management of change (MOC)	Understanding of importance of management of change and agreeing MOC approach to be used.	x	x	x	Marine Corporate personnel, Terminal management, Supervisors, Operators, PIC
G7	Pre-Planning	External Environmental Conditions - Metocean	Ability to define metocean limits for operations at both existing berths / docks and also for ship transfers at anchorages	x	-	-	Marine Corporate personnel, Terminal management, PIC
G8	Pre-Planning	External Environmental Conditions - Metocean	Ability to determine the metocean environmental loads on the offloading system so that the system can operate safely, without damage in the intended conditions. Pre-planning team to have the competence to establish limits. Port & Vessel personnel to have the competence to monitor and take appropriate action if deviations occur during offloading	-	-	-	Marine Corporate personnel, Terminal management, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
G9	Pre-Planning	External Environmental Conditions - Metocean factors	Familiarity with various metocean factors that could affect operations including: • Tides • Current – speed and direction • Wind – speed and direction • Wave – height and period, including swell • Temperature – extremes can affect loading and unloading • Typhoons, hurricanes, tropical storms, squalls, electrical storms. • Visibility factors such as fog, night time conditions (anchorage), etc.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC
G10	Pre-Planning	Anchorage – Pre Planning	During pre-planning, knowledge of local conditions, utilisation of anchorage areas and marine operations / traffic to determine means / plans to minimise the impact of an LCO_2 leak or spill when undertaking offloading.	-	-	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC, Port authorities
G11	Pre-Planning	External Environmental Conditions - Anchorage	Knowledge of prevailing winds and metocean conditions especially seasonal influences.	x	-	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC, Port authorities

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
G12	Pre-planning	Marine / Interface risks	Understanding of and planning for potential emergency scenarios including breakaway of transfer hoses / arms under extreme wind or wave conditions.	x	x	x	Marine Corporate personnel, Terminal management, supervisor, operator, PIC, Port authorities
G13	Pre-planning	Quality and Quantity	Understanding the quantity and quality requirement to be met part of the transfer of ownership and to ensure safe processing and mixing with other batches at the storage facility.	x	-	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC, Port authorities
G14	Pre-planning	Quality and Quantity	Knowledge of sampling, including vaporization. Process and ability to interpret sample results. Understanding of what trouble shooting measures can be undertaken if necessary.	x	x	-	Terminal management, supervisor, operator, PIC
G15	Pre-planning	Quality and Quantity	Knowledge of recordkeeping requirements related to quality and quantity of LCO_2 being offloaded.	x	-	-	Terminal management, supervisor, PIC
G16	Pre-planning	Quality / Quantity	Knowledge of quality requirements / product specifications for LCO_2 stored, transferred, and offloaded.	x	-	-	Marine Corporate personnel, Terminal management, supervisor, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
G17	Pre-planning	LCO_2 Offloading Procedures - Planning	Understanding of various factors to be considered during compatibility and interface review for LCO_2 offloading operations. This includes ship particulars for offloading and LCO_2 receiving vessels including interfaces between two vessels. Similar information / reviews needed for interface with terminals.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, PIC
G18	Pre-planning	LCO_2 Offloading Procedures - Planning	Understanding of information to be provided to local Port Authorities regarding offloading operations. This will allow Port to arrange any resources (personnel, emergency services) to support operation.	x	-	-	Terminal management, supervisor, PIC
G19	Pre-planning	LCO_2 Offloading Procedures Mooring operations	Understanding of standard mooring arrangements including the potential impact of weather conditions as well as any unique aspects due to the presence of LCO_2 onboard offloading vessel. Mooring could be to pier or StS.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, PIC, Port authority.
G20	Pre-planning	Marine criteria	For StS offloading operations, knowledge of factors that would impact approach, mooring and unmooring and impact positioning of vessel to conduct offloading / loading / transfer operations. These could include loads / arrangement, berthing and fendering requirements, alignment of the vessels, etc.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, PIC, Port authority
G21	Pre-planning	LCO_2 Offloading Procedures Control Zones	Personnel involved with planning, to understand the requirements for setting up three different types of control zones: Safety zones, security zones, marine zones including the purpose and requirements of each.	x	-	-	Marine Corporate personnel, Terminal management, supervisor, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
G22	Pre-planning	Safety / environmental equipment	Ability to ensure all safety and environmental equipment is available and accessible prior to the start of operations (both hardware and PPE)	x	-	-	Terminal management, supervisor, PIC
G23	Pre- planning	Test and Inspect	Understanding the requirements and scope of a pre-operation inspections and testing. Ability to identify any non-compliances. This would include LCO_2 systems and equipment as well as safety devices such as alarms, ESD, ERC, QC/DC, SSL.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, PIC
Offloading Systems / Equipment Operations							
H1	Offloading Systems / Equipment Operations	Overall design and operational principles	Overall knowledge of LCO_2 operating principles associated with ship / terminal systems and equipment used for loading / offloading, transfer and storage of LCO_2.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, PIC
H2	Offloading Systems / Equipment Operations	Overall design and operational characteristics	Overall knowledge of ship / terminal systems and equipment used for loading / offloading, transfer, and storage of LCO_2.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
H3	Offloading Systems / Equipment Operations	LCO_2 systems and equipment - shipboard	Understanding of engineered processes, systems and equipment associated with LCO_2 storage, transfer and loading / offloading include compression, dehydration, and liquefaction. This includes: • Compressors and pumps (discharge and booster) • PBU units • Heat exchangers • Driers • Onboard storage tanks (above or below deck; ISO tank containers) as applicable. • Reliquefaction plants / BOG handling systems (associated with low pressure tanks) • Piping and valve system – including requirements for rigid and flexible insulated piping).	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC
H4	Offloading Systems / Equipment Operations	Lifting appliances	Understanding of any new requirements for use of marine lifting appliances/ loading arms associated with LCO_2 related operations (offloading hoses, vaporised CO_2 return lines).	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC. Port support personnel (such as cranes operators)

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
H5	Offloading Systems / Equipment Operations	LCO_2 systems and equipment - ashore	For operations ashore, understanding of engineered components including: • Custody transfer metering systems with flow meters • Liquid bulk storage tanks, as applicable • Piping and valving systems • Vaporization equipment to send CO_2 gas back (via vapor return line) to offloading ship's onboard tank	-	-	-	Terminal management, supervisor, operator, PIC
H6	Offloading Systems / Equipment Operations	LCO_2 safety systems and equipment - shipboard	Understanding of engineered safety systems including indicators, controls and alarms such as: • Tank level indication and control • Tank overflow control • Tank pressure indication and control (also relief valves) • Tank vacuum insulation protection • Temperature indication • Gas detection • ESD System including any ship-to-shore links.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
Connect / Disconnect operations							
I1	Connect / Disconnect operations	LCO_2 Offloading Procedures - Establish offloading connection	Understanding of how to position hose handling equipment, such as cranes, lifting appliances and supporting structures, or fixed pipe loading arms to ensure easy connections and safe disconnections (in case of an ERS activation)	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC, Port support personnel (such as cranes operators)
I2	Connect / Disconnect operations	Marine infrastructure – shoreside lifting appliances	For relevant shoreside personnel, knowledge of lifting operations and capabilities/limitations of lifting appliances and related equipment like transfer hoses, connections, manifolds, ESDs. Limitations would include reach envelopes.	-	-	-	Terminal management, supervisor, operator, PIC, Port support personnel (such as cranes operators)
I3	Connect / Disconnect operations	Marine infrastructure – shipboard lifting appliances	For shipboard personnel, knowledge of lifting operations and capabilities/limitations of lifting appliances and related equipment like transfer hoses, connections, manifolds, ESDs. Limitations would include reach envelopes.	x	x	-	Marine Corporate personnel, PIC
I4	Connect / Disconnect operations	Marine infrastructure – Safety device	Understand the purpose of an insulating flange / sleeve in LCO_2 transfer hose.	x	x	-	Marine Corporate personnel, Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
I5	Connect / Disconnect operations	ISO tank container lifting infrastructure	Ability to use a pre-lifting operations checklist to ensure ISO tank container has been prepared properly for offloaded to facility or truck	x	x	-	Terminal management, supervisor, operator, PIC
I6	Connect / Disconnect operations	ISO tank container lifting infrastructure	Ability to replace full ISO tank container with an empty ISO tank container to be used for future LCO_2 storage.	-	x	-	Terminal management, supervisor, operator, PIC
I7	Connect / Disconnect	Shoreside Personnel	Ability to ensure that shoreside personnel involved in lifting operations shall be competent (and certified as appropriate) as per local regulations where the lift will occur.	-	-	-	Terminal management
I8	Connect / Disconnect	Shoreside Personnel	Ability to ensure that operators of lifting appliances shall be familiar with and competent in the operation of the StS crane that they are required to operate. This includes understanding the design, layout, operating functions, and maintenance and inspection requirements of the appliance.	-	-	-	Terminal management, supervisor. Shoreside support personnel
I9	Connect / Disconnect	Shoreside Personnel	Shoreside / terminal persons either operating, rigging, or inspecting cranes and auxiliary equipment, to be knowledgeable about the tasks they will conduct and meet all regulatory competency requirements for the jurisdiction that the task is undertaken.	-	-	-	Terminal management, supervisor, Shoreside support personnel
Offloading Operation							
J1	Operations	LCO_2 Offloading Procedures – Plan and monitor	Ability to follow and adhere to Offloading Plan. This would include ability to recognize anomalies, respond and report issues when necessary.	x	x	-	Terminal supervisor, operator, PIC, Shoreside support personnel

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
J2	Operations	LCO_2 Offloading Procedures – Plan and monitor	Familiarity with detailed transfer processes / procedures specific to a particular offloading operation between specific entities. For example, specific transfers between LP and MP systems (for StS or ship-to-shore operations).	x	x	-	Terminal supervisor, operator, PIC
J3	Operations	LCO_2 Offloading Procedures – Plan and Monitor	Understanding of various conditions to be met before and during transfer. This would range from operating parameters to mooring, marine environmental and weather conditions.	x	x	-	Terminal management, supervisor, operator, PIC, Shoreside support personnel
J4	Operations	LCO_2 Offloading Procedures – Plan and monitor	Understanding of operations required for safe and environmentally sound loading / offloading, transfer, and storage of LCO_2.	x	x	-	Terminal management, supervisor, operator, PIC, Shoreside support personnel
J5	Operations	LCO_2 Offloading Procedures – Plan and Monitor	Ability to monitor on going conditions on board vessels and terminals to assure safe and environmentally sound operations.	x	x	-	Terminal supervisor, operator, PIC
J6	Operations	LCO_2 Offloading Procedures – Plan and Monitor	Ability to monitor on going conditions in established safety, security, and marine zones and hazardous areas onboard and ashore.	x	x	-	Terminal supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
J7	Operations	LCO_2 Offloading Procedures - Communications	Ability to establish and maintain effective communications between various participants throughout offloading, transfer and loading operations. This would include agreement of established channels, means and protocols of communications.	x	x	x	Terminal management, supervisor, operator, Port authorities, Shoreside support personnel
J8	Operations	LCO_2 Offloading Procedures – Drying LCO_2 Piping	Relevant personnel on board vessels and at terminals to have understanding of risks associated with impact of water contact with CO_2 to form carbonic acid and the importance of dehydration / drying processes.	x	x	-	Terminal management, supervisor, operator
J9	Operations	LCO_2 Offloading Procedures - Drying LCO_2 Piping	Knowledge of steps required to dry piping prior to the commencement of introduction of LCO_2 to system. This would include piping isolation, depressurization, use of dry gas, hazards associated with type of dry gas used, monitoring of humidity levels.	x	x	-	Terminal supervisor, operator, PIC
J10	Operations	LCO_2 Offloading Procedures - Drying LCO_2 Piping	Understanding of need to and process for piping pressure / leak testing prior to commencing operations.	x	x	-	Terminal supervisor, operator, PIC
J11	Operations	LCO_2 Offloading Procedures - Cooling down and Ramping up Flow	For personnel onboard supply / receiving vessel or at storage facility, understanding of process for cooling down LCO_2 offloading piping and tank. This would include understanding of temperature, pressure and flow requirements and management, as well as vapour / BOG management.	x	x	-	Terminal supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
J12	Operations	LCO_2 Offloading Procedures – Cooling down and Ramping up Flow	For vessel and terminal personnel, understanding of thermodynamic properties of CO_2 and the properties and hazards associated of the various phases of CO_2 (liquid, gas, solid).	-	-	-	Terminal management, supervisor, operator, PIC
J13	Operations	LCO_2 Offloading Procedures	Understanding of situations where heating may be required such as on the booster pump discharge of LCO_2 receiving vessels to send on-spec LCO_2 to bulk liquids terminal. Also use of heating with vaporisers.	x	x	-	Terminal management, supervisor, operator, PIC
J14	Operations	LCO_2 Offloading Procedures – Transfer	For personnel onboard supply / receiving vessel or at storage facility, understanding of processes required for monitoring and control for safe transfer of LCO_2 during offloading. This would include understanding of temperature, pressure and flow requirements and management, as well as vapor / BOG management.	x	x	-	Terminal management, supervisor, operator, PIC
J15	Operations	LCO_2 Offloading Procedures - Completion of filling	Supply / Receiving vessel personnel. Knowledge of supply / receiving tank unloading, loading, and filling limits. Familiarity with tank alarm setpoints. Understanding of requirements and process for calculating both filling limits and loading limits independently. Understanding of the impacts of relative densities and temperatures on loading limits.	x	x	-	PIC
J16	Operations	LCO_2 Offloading Procedures - Completion of filling	Terminal. Knowledge of flow rates, pressure and temperature limits for loading and filling limits. Familiarity with alarms including tank alarm setpoints. Understanding of requirements and process for calculating flow rates, filling limits and loading limits independently. Understanding of the impacts of relative densities and temperatures on loading limits.	-	-	-	Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
J17	Operations	LCO_2 Offloading Procedures - Completion of filling	Knowledge of response steps required to avoid two phase flows if loading limit curve is exceeded.	x	x	-	Terminal management, supervisor, operator, PIC
J18	Operations	LCO_2 Offloading Procedures - Finalizing offload, purging and prep for next operation	Ability to conduct calculations to determine residual inventories in loading hoses / arms for onshore piping systems between pier equipment and storage tank.	-	-	-	Terminal management, supervisor, operator, PIC
J19	Operations	LCO_2 Offloading Procedures - Finalizing offload, purging and prep for next operation	Understanding purging requirements such as needed pressure differences between purge gas and the receiving gas pressures (MP ops) during the post offloading operations to ensure complete purging of LCO_2 lines, offloading hoses / arms.	x	x	-	Terminal management, supervisor, operator, PIC
J20	Operations	LCO_2 Offloading Procedures - Draining and Stripping	Understanding of draining and stripping operations to remove all remaining LCO_2 from piping following offloading. This will include understanding how to maintain pressure within transfer lines until all liquid is removed.	x	x	-	Terminal management, supervisor, operator, PIC
J21	Operations	LCO_2 Offloading Procedures – Draining and Stripping	Based on local facility capabilities, understanding method for collecting residual LCO_2 as required by environmental regulations.	x	-	-	Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
J22	Operations	LCO_2 Offloading Procedures – Completion, Disconnection, Stowage of connections	Understanding of the process, including sequencing of actions, for disconnection and storage of offloading equipment.	x	x	x	Terminal management, supervisor, operator, PIC
J23	Operations	LCO_2 Offloading Procedures - Finalizing offload and prep for next operation	Knowledge of inspection requirements following system depressurization upon termination of offloading operations.	x	x	x	Terminal supervisor, operator, PIC
SIMOPS							
K1	SIMOPS	Dropped Objects	Understanding of the implications of dropped objects, such as during lifting, to create a hazardous situation such as LCO_2 release. Familiarity with LCO_2 potential hazards. (It is assumed those operating lifting appliances or cranes will have required competence, training and certifications as required by the relevant regulatory body.)	x	x	x	PIC. Terminal management, supervisor, operator. Port authorities, Shoreside support personnel including crane operators

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
K2	SIMOPS	Operating Plan	Understanding of SIMOPS Plan, including simultaneous actions matrix, restrictions, and work stoppage criteria. Plan should address all potential combinations of operations including: mooring operations, vessel ballasting, cargo operations, fuel bunkering, maintenance, supply and provision operations, other nearby vessel or terminal operations that could impact LCO_2 operations. Personnel to be familiar with their role and responsibilities in the plan and their interfaces with others.	x	x	-	PIC. Terminal management, supervisor, operator, Shoreside support personnel
K3	SIMOPS	Emergency Response	Understanding of changes to Emergency Response Plans to accommodate SIMOPS. This could include rerouting of personnel, vessels or vehicles with regards to access to supply / offloading vessel or attending vessels / barges.	x	x	-	PIC. Terminal management, supervisor, operator. Port authorities, Shoreside support personnel
K4	SIMOPS	Emergency Response	Familiarity with location of emergency response equipment including temporary locations, how to use equipment including PPE and required emergency response actions to protect oneself in the event of an emergency. Management personnel would need to be familiar with information given to various personnel.	x	x	x	PIC. Terminal management, supervisor, operator. Port authorities, Shoreside support personnel
K5	SIMOPS	Risk Assessment	Proficiency in and understanding of risk assessment and management of change processes to identify vulnerabilities, potential consequences of errors and required safeguards needed during various SIMOPS sequences.	x	x	-	PIC. Terminal management, supervisor, operator

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
K6	SIMOPS	Hazards	Familiarity with new potential hazards that could be occur during SIMOPS activities and how these could be mitigated or what response is required (as appropriate to job role). This would include the potential for oxygen displacement with a CO_2 release.	x	x	x	PIC. Terminal management, supervisor, operator. Port authorities, Shoreside support personnel
K7	SIMOPS	Management of Change	Proficiency with conducting management of change processes and ability to institute any temporary changes with vessels, personnel, systems, or equipment to accommodate SIMOPS. This could include providing emergency response equipment or PPE in a temporary location to facilitate access.	x	x	-	PIC. Terminal management, supervisor, operator
K8	SIMOPS	Communications	Ability to coordinate with all involved including vendors, contractors, and support organizations to accommodate and coordinate SIMOPS activities.	x	x	-	PIC. Terminal management, supervisor, operator
K9	SIMOPS	Communications	Ability to recognise and communicate changes to conditions during SIMOPS activities.	x	x	x	PIC. Terminal management, supervisor, operator. Port authorities, Shoreside support personnel

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
K10	SIMOPS	Coordination	Ability to coordinate various organizations and various personnel, including specialists such as mooring masters, fuel bunkering personnel, tugs, crane operators, truck / forklift drivers, emergency responders, etc. during SIMOPS to ensure one person maintains overview of all operations. Coordination skills must also include ability to accommodate changes in personnel based on working hours, watch / shift changes, or fatigue. Coordination requirements should also be addressed in pre-planning phase for LCO_2 operations. The decisions on roles and coordination would be documented in the SIMOPS plan. Temporary adjustments would be documented in MOC paperwork.	x	-	-	PIC. Marine Company management. Terminal management
K11	SIMOPS	Impact on Zones	Understanding of the impacts on and modifications needed for safety, security and marine zones with SIMOPS. Ability to document and communicate anticipated changes, even temporary, to all involved parties.	x	x	-	PIC. Marine Company management. Terminal management, supervisor, Port authorities
ISO Tank Container							
L1	ISO tank container	Loading / Unloading ISO tank container	The competencies for this should be set by the national regulations in the country where the storage facility is located and lifting / container operations take place.	x	x	-	Terminal management, supervisor, operator, PIC
L2	ISO tank container	Connect / Disconnect	Understanding of the processes for connecting and disconnecting components, equipment, piping, and electrical supplies / utilities related to LCO_2 loading / offloading operations.	x	x	-	PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
L3	ISO tank container	Loading / Unloading ISO tank container	Knowledge of requirements for preparing for lifting operations (disconnection with vessel systems) and arrangements for lifting of the ISO tank container on / off the vessel. This would include understanding the protocols associated with the fastening / lifting arrangements and any special LCO_2 considerations.	x	x	-	Terminal management, Supervisors, Operators. Port Authorities, Shoreside support personnel, PIC
L4	ISO tank container	Loading / Unloading ISO tank container	Understanding of various aspects of the ISO tank container loading / lifting plan including inspections of the containers and lifting equipment, communications, roles / responsibilities of all parties involved.	x	x	-	Marine Corporate shoreside, Terminal management, supervisor, operator, Shoreside support, PIC
L5	ISO tank container	Communications	Understanding of communication channels and protocols to be use during operations. Ability to use assigned communication devices.	x	x	x	Terminal management, Supervisors, Operators, Port Authorities, Shoreside support personnel, PIC
L6	ISO tank container	Standard Operating Procedures (SOPs)	Familiarity with SOPs related to truck operations for ISO tank container operations including necessary communications before moving the truck.	-	-	-	Terminal Supervisors, Operators, Shoreside support personnel, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
L7	ISO tank container	Pre-planning for replacement	Ability to set standards for acceptable ISO tank container replacements once ship's ISO tank container is sent ashore.	-	-	-	Marine Corporate shoreside, Terminal management
Maintenance							
M1	Maintenance	Incompatibility	Knowledge of metallurgical and materials requirements / incompatibilities specific to LCO_2 components, equipment, system including tanks and piping.	x	x	-	Terminal management, supervisor, operator, PIC
M2	Maintenance	Methods	Knowledge of maintenance / repair methods for components in LCO_2 service.	x	x	x	Terminal management, supervisor, operator

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
M3	Maintenance	Maintenance	Understanding of any unique maintenance requirements associated with LCO_2 systems and equipment such as: • Safe work practices to enter areas where LCO_2 could be present. This could include enclosed / confined space entry as well as lock-out tag out, etc. • Special considerations related to metals / materials to be used – concerns related to low temperature conditions, potential corrosion, pressure requirements. o Discharge and booster pumps. o Compressor parts: stainless steel with corrosion resistance o Compressor piston rings of polytetrafluoroethylene (PTFE) o Plate type heat exchanger plates with nitrile rubber joints. o Piping – stainless steel with corrosion resistance. Valves and other components with corrosion resistance • Requirements for inspections and repairs following testing, loading / offloading. This would include hoses and fittings for connections.	x	x	x	Terminal management, supervisor, operator
M4	Maintenance	Maintenance	Ability to safely isolate system components to allow maintenance. Understanding of relevant safe work practices including risk assessment, confined space, work permits and LOTO.	x	x	-	Terminal management, supervisor, operator, PIC

Sl No.	Overall Topic	Topic / Operation	Competency	Mgmt Ship Senior Officers	Ops Ship Junior Officers	Support Ratings	Other Marine Corporate / Shoreside
M5	Maintenance	Maintenance / supply chain	Understanding that specific equipment / part, including pipeline, materials must be provided that are resistant to corrosion caused by acidic environments. This would include supply chain / ordering personnel understanding substitutions must be avoided and such personnel are familiar with approval processes needed to change an order.	x	x	-	Marine Corporate shoreside, Terminal management, supervisor, operator
M6	Maintenance	Maintenance / supply chain	Understanding that only certain non-metallic components can be used in LCO_2 service, particularly in pipelines. It must be understood that certain components must be certified for LCO_2 service to ensure their continued integrity especially where impurities could be present in the LCO_2 stream.	x	x	-	Marine Corporate shoreside, Terminal management, supervisor, operator

8.4 Discussion/ Context

For shipboard personnel, the existing STCW requirements for minimum standards of competence in training for ships subject to the IGF Code served as a starting point for identifying competencies and training for liquid CO_2 related operations. The identified LCO_2 competencies supplement but do not replace those shipboard staff would hold for serving on the vessel upon which they serve whether that be a tanker ship, bulk carrier or container vessel.

With regards to shipboard personnel, given the nature of the operations on different vessel types, it may be possible that the amount of additional training needed to achieve CO_2 competency may be greater for some vessels than for others. Tanker ships, for example, commonly carry hazardous cargoes and personnel on board may be familiar with offloading operations from the tanker ship-to-bulk liquid terminals via pipelines. In addition, tanker ship personnel undertake additional training under STCW (Chapter V – Standards regarding special training requirements for personnel on certain types of ships) depending on the type of cargo carried: oil, chemical or LNG. The competencies outlined for tanker personnel's additional STCW training have strong parallels to what would be needed for conducting LCO_2 operations.

Container vessels and bulk carriers often carry a variety of cargoes, including in some cases, dangerous goods and deliver these to various terminals. These vessels, however, do not normally offload liquid cargoes via piping systems to other vessels or to terminals. With that said, the current plan is that container vessels will carry LCO_2 stored in ISO tank containers that will be offloaded on to rail cars or trucks for transportation and later, storage ashore. It is expected that some of the container offloading / lifting operations for the ISO tank containers could be similar to operations used for other cargoes. As a result, it is possible, some tanker or container personnel may have prior experience (and competence) with certain aspects of LCO_2 operations that will be associated with unloading / loading, storage and / or transfer of LCO_2. It is not expected that bulk carrier personnel will have prior operational experience similar to that required for LCO_2 as discussed in this report.

With regards to CO_2 itself, most vessels carry CO_2 onboard as a fire extinguishing substance so shipboard personnel will have some familiarity with it. They will not have experience with LCO_2 stored in large quantities in a tank for offload so past CO_2 knowledge, understanding and proficiency will need to be enhanced. As a result, the proposed competencies should be viewed through the lens of prior operational experience which could influence time requirements for personnel achieving competency.

Regardless, all personnel on board ships carrying captured LCO_2 would need to obtain knowledge, understanding, proficiency or familiarity (as appropriate to their position) with regards to CO_2 unloading / loading, handling, storage, transfer, and emergency response operations. There is an assumption that since it is expected that LCO_2 will require proficiency with computer-based interfaces and control systems that personnel serving onboard ships carrying LCO_2 will either have experience with such systems or will obtain these skills.

For those serving on LCO_2 receiving or floating CO_2 storage vessels, it is assumed these shipboard personnel would hold certifications and have achieved competencies related to the IGC Code. In this case, it is possible that the competencies provided specifically for CO_2 risks, hazards and related cargo operations would need only to be met and supplement the seafarer's previous training and experience with liquefied gases in bulk if no CO_2 background exists. Regardless, it is recommended that companies operating vessels under the IGC Code, conduct a gap analysis between their current training requirements and the information provided here to identify any outliers.

It is also assumed that vessels, such as bulk carriers, that will be involved with transfers at anchorage, may have personnel on board with competencies, training, and experience with StS fuel transfers however such experience would need to be supplemented with LCO_2 operations specific training prior to undertaking StS LCO_2 offloading / transfer operations. If such StS experience does not exist, then such personnel will need to understand StS as well as LCO_2 specific requirements.

As with any type of operation where two (or more) organisations must coordinate, the transfer of captured CO_2 from a ship to another vessel or to a terminal will require competent personnel involved from each organisation. While the information provided in this report for shipboard personnel does outline competencies related to such interfaces further details regarding coordination competencies are provided in the section of this report entitled “LCO_2 Handling Competency Information – Shipboard and Shoreside Personnel”.

Since the onshore storage of LCO_2 would be a commercial endeavour, it is assumed that the terminal management would ensure that its facility and workforce meet relevant regulatory requirements, to support safe and environmentally sensitive operations. For terminal personnel, this would mean ensuring that are competent and that any required regulatory training and certification has been taken place and that personnel are knowledgeable about the terminal company’s safety and environmental policies, procedures, and practices.

Safe, efficient, and well-integrated operations hinge upon building on shipboard and shoreside personnel’s existing training, current related experience and integrating that with LCO_2 competencies such as those provided here.

The information provided through the LCO_2 Handling Competency Information – Shipboard and Shoreside Personnel competency matrix should provide an overview or more wholistic definition of the needed competencies, the interactions and interfaces associated with moving captured LCO_2 from its origin on a ship to a storage facility onboard a ship or ashore.

The information in this part of the report outlines what will be required of various personnel regarding LCO_2 / CO_2 knowledge, understanding, proficiency and familiarization. It also outlines the complexity and interdependencies of the operations.

The sets of identified competencies from this report must also be viewed as supplemental to existing job requirements and only highlight what additional subjects must be addressed that are unique to LCO_2 / carbon dioxide. As stated earlier, it was assumed during this project that both shipboard and shoreside personnel come to the workplace with competency in their current job functions and that the information provided in this part of the report will be used to augment already existing competency and training frameworks such that LCO_2 operations can be safety and successfully completed.

9. Readiness of Current Infrastructure for Liquefied CO_2 Offloading

9.1 Overview

This part of the report describes our review of the readiness of current infrastructure for LCO_2 offloading (i.e., facilities that can be used as is or with modifications or as new assets) relating to the four offloading concepts defined earlier in chapter 3. The information presented in this chapter is based on available data up to December 2023.

There are limited publicly available examples of existing terminals handling CO_2 as a product in ports. Nonetheless, the concepts developed as part of this study aimed to integrate offloading of onboard captured LCO_2 with existing port infrastructure as far as practical. The potential remains for modifying or upgrading existing port facilities for pilot projects or near-term applications.

Table 9.1 and Table 9.2 summarise the perceived high-level feasibility for using, adapting or upgrading existing terminal types to accommodate each offloading concept. This chapter discusses each in turn.

Table 9.1 – Suitability of infrastructure for offloading concepts

Existing port / terminal type	Concept 1 (Ship-to-liquid bulk terminal)	Concept 2 (Ship-to-FCSU with intermediate LCO_2 receiving vessel)	Concept 3 (Ship-to-liquid bulk terminal with intermediate LCO2 receiving vessel)	Concept 4 (Ship-to-terminal with ISO tank containers)
Existing bulk CO_2 terminals	Refer to Section 9.2	n/a	Refer to Section 9.2	n/a
Planned bulk CO_2 terminals	Refer to Section 9.3		Refer to Section 9.3	
Existing bulk liquid terminals	Refer to Section 9.5.1	n/a	Refer to Section 9.5.1	n/a
Existing container terminals	n/a	n/a	n/a	Refer to Section 9.5.3
Ports without liquid bulk terminal	n/a	Refer to Section 9.5.2	n/a	n/a

Table 9.2 – Key for Table 9.1

n/a	Not applicable
	Not likely to be feasible
	May be feasible
	Likely to be feasible

9.2 Existing LCO_2 Transport Infrastructure

This section reviews the existing ports around the world that handle CO_2 and provides a general overview their capability, based on publicly available information and information supplied by study partners and stakeholders. There is currently very limited existing infrastructure for liquid CO_2 transfer [1], with none currently in operation in the same scale or manner described by the concepts in this study. The only exception is isolated examples of offloading LCO_2 ISO tank containers. LCO_2 transport in ports appears to be focussed on the food industry, with many key differences in the specification of their product that pose a challenge in the uptake of the offloading concepts for onboard captured CO_2. Information on other facilities around the world has been difficult to acquire outside of Europe due to limited published information.

9.2.1 Nippon Gases – Tilbury, Warrenpoint & Teesside Ports, UK [2]

These ports are currently operational, serving food-grade CO_2 to the carbonated drinks industry. CO_2 is transported in liquid form, with loading and offloading infrastructure available at all three ports of Tilbury, Warrenpoint and Teesside. The current infrastructure consists of the following:

- Loading arm for transfer
- 150-200 tpd 6” liquid line operating at 15 bar
- Refrigeration system suitable for CO_2 use (no NH_3 refrigerants)
- 3” vapour return line
- ISO tank container crane
- Liquid CO_2 storage tanks

Figure 9.1 – Warrenpoint Harbour Facility [3]

Whilst this infrastructure is currently in use for the food industry, it is of a similar nature to what would be required for the offloading concepts discussed in this project. The challenges that may be faced here in using or adapting the facilities for onboard captured CO_2 relate to the specification and purity of the CO_2. Food grade CO_2 storage is of a much higher grade (as discussed in Section 0), meaning that any produced from carbon capture onboard of ships would require analysis and potentially post-treatment before it could be stored in these tanks.

To serve these ports, Nippon Gases currently have four ships in operation which are also all equipped to perform StS liquid CO_2 transfer. All three of these ports also have cranes for ISO tank container transfer. Warrenpoint uses mobile harbour cranes with a spreader attachment to offload containers. Tilbury and Teesside have Ship-to-Shore cranes to move containers at dedicated container berths. The London Container Terminal is located at Tilbury, one of the UK's largest container terminals, serving a wide variety of industries with 11 container cranes [4].

In order for a pilot study to take place at one of these locations, more investigation would be required into the compatibility of food grade CO_2 offloading infrastructure with onboard captured CO_2, which is likely to be of a significantly lower standard, as discussed in Section 0.

9.2.2 Loviisa Port - Finland

The Loviisa Port has a ship transfer manifold specifically for loading of bulk CO_2 carriers. CO_2 trucks have onboard pumps which connect to the manifold to fill the GERDA liquid CO_2 vessel. Given that the loading takes place directly from these trucks, new infrastructure (piping and storage units) would likely be required at this facility to allow offloading at the scale required for the proposed offloading scenarios. GERDA's CO_2 is used in the beverage business (carbonation), food business (chilling, freezing), air catering (cold chain assurance) and greenhouse businesses [5].

Figure 9.2 – GERDA vessel loading LCO_2 from trucks [5]

9.2.3 Food Industry CO_2 Terminal

For CO_2 to be fit for human consumption in the food or beverage industries, a higher grade is required than typical industrial applications. Industrial feedstocks may use 99.5% pure CO_2 whereas the food and beverage industry would require a minimum of 99.9% pure CO_2, as shown in Table 9.3.

Table 9.3 – CO_2 purity chart [6]

Grade	Purity	Other Gases
Research	99.999%	0.001%
Supercritical Fluid	99.998%	0.002%
Laser	99.95%	0.05%
Anaerobic	99.95%	0.05%
Beverage	99.9%	0.01%
Food	99.9%	0.01%
Bone Dry	99.8%	0.02%
Medical	99.5%	0.5%
Industrial	99.5%	0.5%

Comparing these figures with the required specification of CO_2 from the Aramis project, shown in **Error! Reference source not found.** where a minimum of 95% pure CO_2 is required from captured sources, shows the gulf in quality between the source and end user. This creates a challenge of introducing new infrastructure to guarantee the required quality where the end user is not sequestration. Whilst the purification of CO_2 is done using mature technology and an established industry, this will add extra cost and operational complexity to the process, with equipment costs that may include those listed below [7]:

- Oil filters
- Gas scrubbers
- Drying and adsorption columns
- Metering & analysers

Given these factors, it is likely that any facility using the concepts discussed in chapter 3 would likely require segregated systems, such as a control system, a dedicated safety system, additional utility systems, loading arms and storage tanks, to meet capacity requirements and to avoid cross-contamination.

9.3 Planned LCO_2 Transport Infrastructure

Table 9.4 below shows some of the planned projects happening around the world to develop LCO_2 infrastructure. These projects are located nearby to, or with transport links to, industrial clusters that are emitters of CO_2 which can be captured. These terminals then transport the LCO_2 to storage solutions such as sequestration or using novel technology for storage such as the Carbfix Coda terminal.

Table 9.4 – LCO_2 infrastructure projects

Location	Scale	Key Dates	Key Stakeholders	Notes
Bremerhaven Port [8]	Not yet published	"Several years" before operation	CO_2 Management AS (CO_2M), bremenports GmbH	The company CO_2 Management AS is planning to build a carbon dioxide transshipment hub in Bremen for subsequent usage or geological storage of the CO_2. The gas would be collected in liquefied form from various industrial sites for further usage or loaded onto ships and subsequent exported to permanent storage facilities.
Port of Gdansk [9]	2.7mtpa CO_2 by 2025, 8.7mtpa by 2030	Operational by 2025	Air Liquide Polska, Zarzad Morskiego Portu Gdansk, PKN ORLEN, Lafarge Cement, Sogestran Shipping	Open access multi-modal LCO_2 import-export terminal in Port of Gdansk with related CO_2 transport infrastructure from the facilities of emitters to European CO_2 transport and storage network in the basin of North Sea with a use of transport via roads, railways, pipelines and ships
Northern Lights [10]	800ktpa CO_2 up to 5mpta in the second development phase	Operational by 2025	Equinor, Shell and TotalEnergies	Captured and liquefied CO_2 from UK/ European emitters will be loaded and delivered to the receiving terminal in Øygarden onboard CO_2 transportation ships.
Port of Gothenburg [11]	4mtpa CO_2	Operational by 2025 (1 ship)	Nordion Energi, Göteborg Energi, Renova, Gothenburg Port Authority, Preem, and St1.	Develop the logistics chain required to transport captured carbon dioxide from different industrial facilities in western Sweden – from liquefication and intermediate storage, through to distribution to ships and onward transport to the repository site.
Severnside CCS hub Bristol [12]	800k – 1mtpa CO_2, rising to 4mtpa CO_2 in 2035	Operational by 2027-2028 (1 ship)	Numerous local emitters	The hub will collect CO_2 at scale using a fleet of ships to transport CO_2 onwards for long term geological storage.

Location	Scale	Key Dates	Key Stakeholders	Notes
Carbfix Coda Terminal, Iceland [13]	20,000 m^3 per ship, 500ktpa CO_2, rising to 2mtpa in 2031	Operational by 2026-2028 (1 ship)	Reykjavík Energy	The CO_2 will be imported from industries with carbon capture capabilities across North Europe. There, the CO_2 will be compressed and transported by specifically designed gas carriers in a cold liquefied form.
Port of Immingham [14]	Not yet published	Operational by 2027	Harbour Energy new terminal will be connected to Harbour Energy's CO_2 transport and storage network, which is called Viking CCS. Burton Energy, Phillips 66 and VPI are partners of the Viking CCS network	Associated British Ports ABP intends to develop new infrastructure at the port, including a jetty, to handle the import and export activities of liquid bulk products. Link CO_2 emissions from industrial businesses across the UK to Viking CCS's high-capacity CO_2 storage sites in the Southern North Sea.
Project Aramis, Maasvlakte, Port of Rotterdam [15]	22 mtpa CO2 by 2030	Final investment decision (FID) 2025, first operation by 2028	TotalEnergies, Shell, Energie Beheer Nederland (EBN) and Gasunie	Liquid CO_2 offloading from vessels at 13-18 bar before transfer to offshore platforms where it is sequestered. Very precise specification of CO_2 is required.
CO_2Next Terminal, Port of Rotterdam [16]	5.4 mtpa CO_2 in initial phase	FID 2025, first operation by 2028	Vopak, Gasunie	Open access liquid CO_2 terminal for the reception and delivery of liquid CO_2 via vessels, trucks or railcars. Infrastructure focused project rather than sequestration market player.
Koole Terminal Botlek, Port of Rotterdam [17]	>2 mtpa CO_2	Under discussion	Horisont Energi	Planned export terminal to connect the Port of Rotterdam to the planned Delta Rhine Corridor CO_2 pipeline

Location	Scale	Key Dates	Key Stakeholders	Notes
Brunsbüttel Port, Hamburg	Not yet published	Under discussion	Unknown	Brunsbüttel is a large container port in Hamburg that is developing a renewable energy cluster. There are currently 3 cranes in place for ISO tank container transfer and an LNG regasification terminal, with discussions currently underway to develop capability for liquid CO_2 transfer.
Port Zhoushan, China	Not yet published	Under discussion	Sinotech and Sinopec	Concept to offload LCO_2 from vessel in ISO tank containers via shuttle truck relying on the successful experience for onshore CCUS by Sinopec.

This table shows that some projects are close to completion such as Northern Lights which can provide useful insight for this study. These projects could also be modified to cater for offloading of onboard captured CO_2, which is discussed further in Section 9.5, however many of these projects are still in concept phase yet to reach FID. This emphasises the infancy of this industry.

Whilst these sites do not explicitly refer to onboard carbon capture, given their location next to the sea and industrial clusters, it is possible that onboard carbon capture could serve as the source of CO_2 in these instances. Further modifications required are discussed in Section 9.5.

9.4 Suitable Locations for Pilot Project

Of all of the project locations listed in Table 9.4, the following three were selected as being favourable for a pilot study for reasons detailed below.

9.4.1 Northern Lights

The most advanced of all the listed projects in terms of progress, Northern Lights already has construction underway with the receiving terminal being built in Øygarden, Norway. Operation is expected to be underway by 2025. The project will sequester CO_2 in North Sea reservoirs meaning that there should be a consistent and profitable demand for offering CO_2 storage as a service. The location of the project will offer a cross-border value chain which makes it an attractive option for onboard CCS integration, given that some of the legal and contractual mechanisms may already be in place to absorb a new internationally captured CO_2 source.

9.4.2 Port of Gdansk

The port of Gdansk has an advantage over some of the other projects in Table 9.4 on planning the capability to both import and export LCO_2. Gdansk will have links to a European storage network and is planning to be operational in 2025, with railway, road and sea transport infrastructure available.

9.4.3 Port of Rotterdam

Project Aramis has the largest targeted capacity for removal of carbon of all projects listed in Table 9.4, at 22 mtpa. The project will have dedicated offshore assets for sequestration meaning legal mechanisms will be in place to accept international transfer. This project will have a great deal of exposure to industrial clusters and maritime trade given its key geographical location. This project is supported by other infrastructure projects happening in the Port of Rotterdam area such as the Koole Terminals export to Norway and also the CO_2 NEXT terminal, as part of the areas intention to become a central hub for CO_2 industries.

9.5 Integration with Existing Terminals

In this section, the modifications required to implement each offloading concept are compared with expected existing infrastructure to highlight potential options and outline challenges. The subsections recap on concept designs to discuss operational aspects.

9.5.1 Liquid Bulk Terminals

Two of the concepts developed in chapter 3 describe transfer of LCO_2 to liquid bulk terminals, using similar infrastructure and equipment to that which is already being used in existing bulk LCO_2 transport facilities. These two concepts are concept 1, shown below in Figure 9.3, and concept 3, shown below in Figure 9.4.

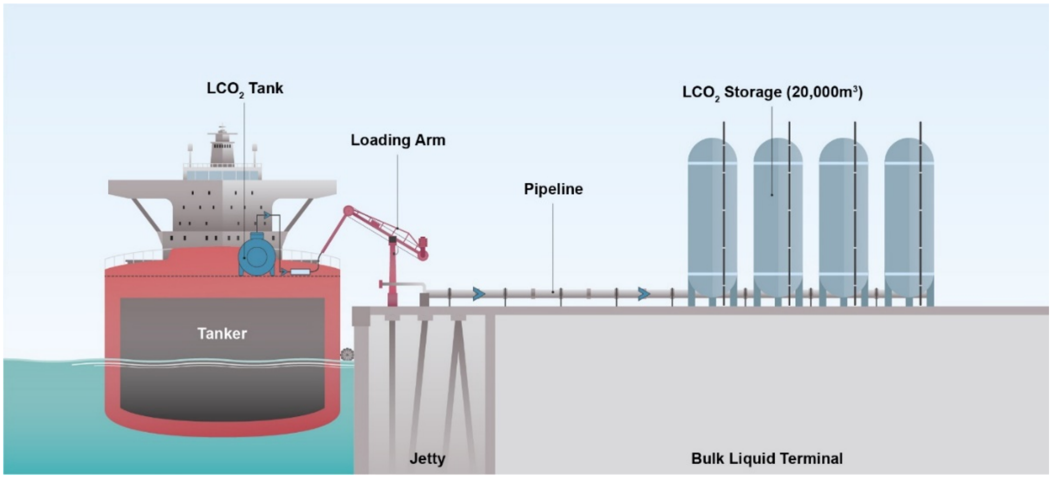


Figure 9.3 – Concept 1 - Ship-to-liquid bulk terminal

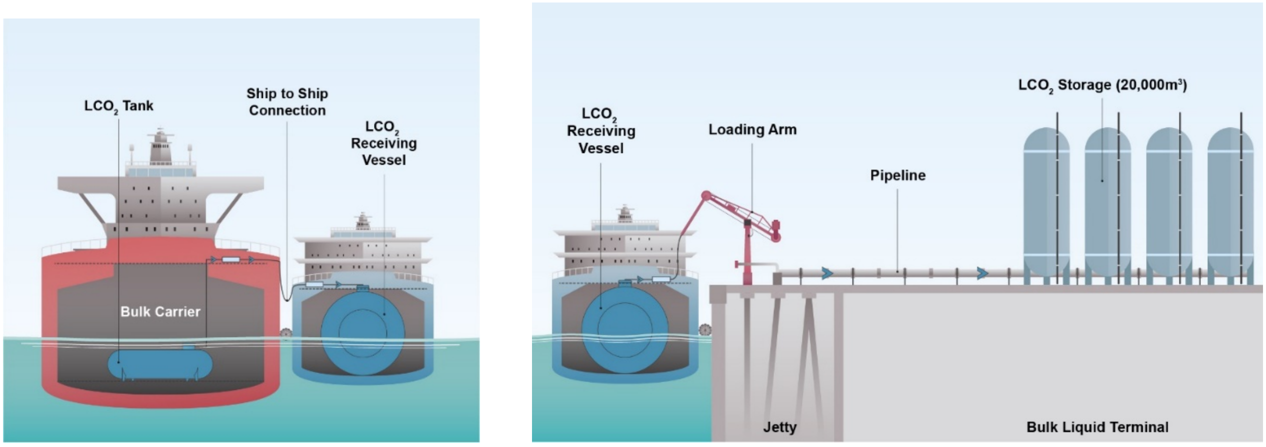


Figure 9.4 – Concept 3 - Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel, stages 1 and 2

Any modifications required to maritime infrastructure at a bulk liquid terminal will be dependent on the type of product and size range of vessels handled at the facility. The jetty and berth infrastructure at a bulk liquid terminal that typically berths large vessels is likely incompatible with the smaller LCO_2 receiving vessels proposed to offload LCO_2 at the same facility (concept 3). For a tanker berthing directly at a bulk liquid terminal to offload both its cargo and the onboard captured CO_2 (concept 1), the jetty and berth infrastructure will likely remain unchanged, given that the terminal is already designed to load/offload the tanker. However, this will be dependent on the vessel's offloading manifold being incorporated in a way that integrates with the terminal's mooring and loading arm arrangement.

The size of vessels expected at liquid bulk terminals for different products is shown in Table 9.5. This shows there is a contrast in the size of vessel at each liquid bulk terminal, which is dependent on the product handled. For example, LCO_2 receiving vessels will have a length of approximately 130m. If one of these vessels is planned for berthing at an LNG bulk liquid terminal, the vessel's geometry will be incompatible with the berth which is designed for a vessel length up to 350m.

Operationally, most bulk liquid terminals are envisaged to be compatible with offloading onboard captured $LCO_{2,}$ as the general operational procedures and infrastructure will be similar. However, there will be a need to develop new safety procedures and associated training to personnel, as discussed in greater detail in chapter 6.

Table 9.5 – Comparison of liquid transfer vessels

Liquid	Vessel length (m)	Vessel beam (m)	Vessel draught (m)	Vessel size
NH_3	119 – 175	19 – 28	8 – 10.5	8,000m^3 – 35,000m^3
LPG	160 - 265	21 – 42	9 – 13.5	10,000 – 60,000dwt
Tanker	185 – 330	32 – 53	11 – 53	50,000 – 185,000dwt
CO_2	~130	~20	~8.5	7,500m^3
LNG	250 – 350	35 – 55	9.5 – 12	50,000 – 125,000dwt

9.5.1.1 Concept 1 - Ship-to-Liquid Bulk Terminal

In concept 1, major modification to jetty and berth infrastructure is not likely required as the tanker vessels will offload LCO_2 at the bulk liquid terminal that they discharge their main liquid cargo.

The key modification required will be to the loading arm infrastructure and pipelines to storage. A new loading arm will likely be required to prevent contamination with other liquid bulk products and to ensure the pipeline infrastructure is suitable for the properties of LCO_2. The dimensions of the loading arm will be in line with existing loading arms at the jetty; the reach of the loading arm should be suitable for tanker vessels. However, this will be dependent on the vessel's offloading manifold being incorporated in a way that integrates with the terminal's mooring and loading arm arrangement. Structural checks may be required to ensure that the jetty trestle is suitable for an additional loading arm and pipeline.

Although tank infrastructure will be in place, it is unlikely to be suitable for LCO_2 storage; new tanks will likely be required. Tank foundations and ancillary equipment may already be available.

9.5.1.2 Concept 3 - Ship-to-Liquid Bulk Terminal with Intermediate LCO_2 Receiving Vessel

In concept 3, modification of jetty and berth infrastructure is likely required due to the difference in dimensions between an LCO_2 receiving vessel and other vessels that a bulk liquid terminal has been designed for. Tank and infrastructure will already be in place.

The dimensions of the vessels carrying NH_3, LPG or similar chemical products are similar to an LCO_2 receiving vessel. Therefore, the infrastructure of these bulk liquid terminal is expected to be more compatible with less modifications. With a terminal normally handling larger vessels, there will be more extensive modifications required, which can be challenging to implement in a busy and hazardous environment. The following modifications are likely required to enable an LCO_2 receiving vessel to berth at a jetty or quayside designed for a larger vessel:

- Geometric checks to ensure the vessel manifolds suitably align with the position of the jetty loading arm.
- Additional fenders and bollards. It is possible that the spacing of fenders and bollards is too large for a smaller LCO_2 receiving vessel.
- Potentially additional dolphins or extensive modifications may be required to existing jetty. The jetty structure may not have suitably located dolphins to accommodate a smaller LCO_2 receiving vessel and allow a suitable mooring arrangement.

Similar to concept 1, concept 3 will require a new loading arm to prevent contamination with other liquid bulk products. The loading arm itself must have sufficient reach to access the manifolds of the small LCO_2 receiving vessels. The loading arm in concept 3 will likely have a longer reach than the loading arm in concept 1. These modifications assume that the existing bulk liquid terminal have capacity to allow offloading via LCO_2 receiving vessels. If a port operator decides that current berth capacity is not sufficient, a new berth may be required at the terminal. This would require capital dredging to create a berth pocket, and new a jetty structure, including bollards, fenders, dolphins and loading arms.

Although tank infrastructure will be in place, it is unlikely to be suitable for LCO_2 storage; new tanks will likely be required. Tank foundations and ancillary equipment may already be available.

9.5.2 Terminals Without Bulk Liquid Infrastructure

For integrating offloading LCO_2 at ports that do not have existing liquid infrastructure, an option is to have an LCO_2 offloading receiving vessel that can act as intermediate storage before transferring the CO_2 to shore storage tanks or to a floating CO_2 storage unit, as per concepts 2 and 3 arrived at previously in chapter 3. This section will explore the present status and technical specifications of LCO_2 carriers that can act as receiving vessels and Floating CO_2 Storage Units.

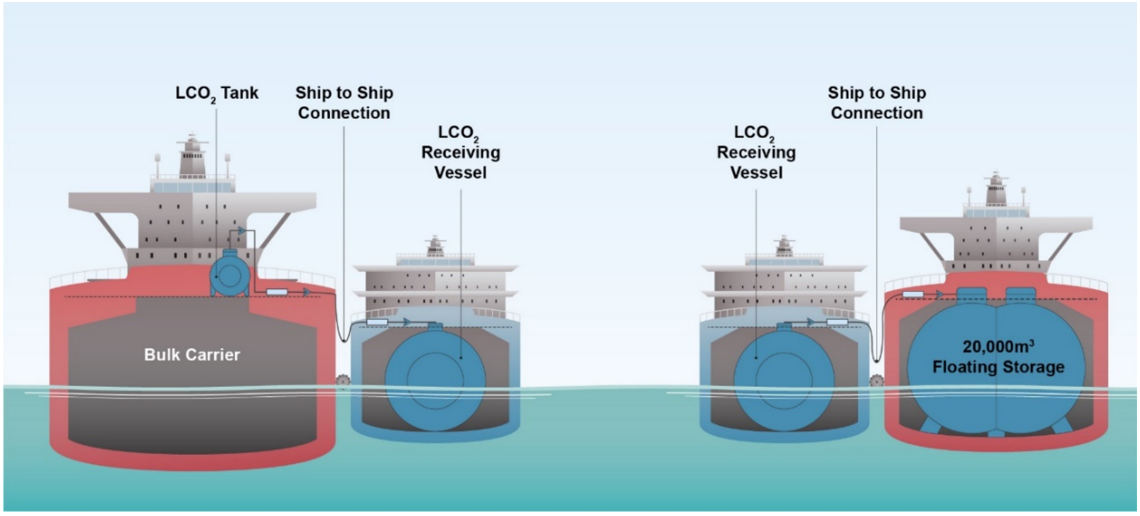


Figure 9.5 – Concept 2 - Ship-to-FCSU with intermediate LCO_2 receiving vessel

LCO_2 carriers are specialised vessels within the IGC framework designed to transport liquid carbon dioxide. Currently, they are used to ship LCO_2 primarily for industrial applications, including the food, beverage, and healthcare industries. The number of dedicated LCO_2 carriers is very limited at present, but with the growing interest and prospects of CCS projects, LCO_2 carriers will play a crucial role in the supply chain to address the reduction of GHG, including offloading of captured LCO_2 from ships and transporting captured CO_2 to suitable storage sites. To address this new trading of reclaimed LCO_2, new shipbuilding projects are being contracted and several other larger size conceptual designs are being proposed to the maritime industry.

Similarly, FCSU and floating CO_2 storage unit with injection capability (FCSU-i) are currently in the conceptual stage to facilitate the final steps into the LCO_2 supply chain, by sequestering CO_2 into offshore fields. Interest in FCSU will increase as the number of CCS projects worldwide grows in the future.

9.5.2.1 LCO_2 Receiving Vessel

In the context of this study, a LCO_2 receiving vessel is basically a small size LCO_2 gas carrier suitable to receive the carbon dioxide in liquefied form from ships fitted with OCCS and transfer the product to shore storage tanks, FCSU or to a larger LCO_2 carriers suitable for longer distance transportation.

LCO_2 carriers are designed to meet the requirements of IGC Code. In accordance with Table of summary requirements in Ch. 19 of the Code [18]. The ship type designated for LCO_2 carrier is 3G. Considering the Code requirements, an existing 2G or 2PG ship type, as defined in the Code, could also be acceptable to carry liquefied CO_2 subject to the tank's design considerations. As explained in chapter 2 of this report, LCO_2 can only be transported in pressurized form so, only ships fitted with Type C tanks are capable for its transport. It is also interesting to note that a LCO_2 ship would not need to comply with some of the requirements for tankers under SOLAS Conventions, as the product intended to be transported is non-flammable. In the case that the LCO_2 carrier is intended for the carriage of other liquefied gases, as listed in Ch.19 of the IGC, the ship will need to comply with all other requirements of the Code applicable to those intended cargoes.

Existing LCO_2 Carriers

At present only a few vessels as per table below are in service for transporting LCO_2 for the food and beverage industry.

Table 9.6 – LCO_2 carriers in service

Vessel Name	IMO No.	Flag / Register	Build year	Builder	Owner	Manager/Operator	Cargo Capacity (LCO_2) - T
Embla	9279446	Norwegian NIS	2005	Bodewes Shipyard, Holland	Nippon Gases Europe Ship	Larvik Shipping AS, Larvik, Norway	1770
Helle	9201906	Norwegian NIS	1999	Frisian Shipyard	Nippon Gases Europe Ship	Larvik Shipping AS, Larvik, Norway	1240
FrCodaoya	9345350	Norwegian NIS	2005	Bodewes Shipyard, Holland	Nippon Gases Europe Ship	Larvik Shipping AS, Larvik, Norway	1770
Gerda	9279410	Norwegian NIS	2005	Bodewes Shipyard, Holland	Praxair Ship, Oslo Norway	Larvik Shipping AS, Larvik, Norway	1770

LCO_2 Carriers on Order

In the recent few months, some new LCO_2 carrier new buildings have been ordered dedicated for CCUS projects.

Table 9.7 – LCO_2 carriers on order

Vessel Name	IMO No.	Flag / Register	Build year	Builder	Owner	Manager/Operator	Cargo Capacity (m^3)
DALIAN NO 1 G7500-1	9954228	Norway	2024	Dalian Shipbuilding Ind - No 1	Northern Lights JV DA	Northern Lights JV DA	7,500
DALIAN NO 1 G7500-2	9954230	Norway	2024	Dalian Shipbuilding Ind - No 1	Northern Lights JV DA	Northern Lights JV DA	7,500
DALIAN NO 1 G7500-3	1034668	Norway	2024	Dalian Shipbuilding Ind - No 1	Northern Lights JV DA	Northern Lights JV DA	7,500

Vessel Name	IMO No.	Flag / Register	Build year	Builder	Owner	Manager/Operator	Cargo Capacity (m^3)
HYUNDAI MIPO 8398	1029974	Marshall Islands	2025	Hyundai Mipo Dockyard Co Ltd	Capital Maritime & Trading	Capital Maritime & Trading	21,560
HYUNDAI MIPO 8399	1029986	Marshall Islands	2026	Hyundai Mipo Dockyard Co Ltd	Capital Maritime & Trading	Capital Maritime & Trading	21,560
EXCOOL	9966336	Japan	2023	Mitsubishi SB Shimonoseki	Kumazawa Kaiun Co Ltd	Sanyu Kisen	1,700

Gas Ships which can be re-purposed as LCO_2 Carriers

There are a few gas ships in service which can be re-purposed as LCO_2 carriers as their cargo tanks are designed for 7 bar and -104°C and they can store LCO_2 at LP conditions. However, it is to be noted that there is a significant difference in the density values between ethane/ethylene (as original intended cargoes for these vessels) and LCO_2. Such difference in density will not only lead to a significant reduction on the capacity of cargo transportation (tanks will not be able to be filled to the maximum capacity) but also it will require that the cargo tanks structure and tank supports will need to be re-evaluated to demonstrate that they are suitable for the heavier cargo density, by performing all relevant calculations for static and dynamic loads, as indicated in the IGC Code.

Table 9.8 – Gas ships which can be re-purposed as LCO_2 carriers

Vessel Name	IMO No.	Flag / Register	Build year	Builder	Owner	Manager/Operator	Cargo Capacity (m^3)
CORAL SHASTA	9254941	Singapore	2003	Hudong-Zhonghua Shipbuilding	GATX Corp	Norgas Carriers Pte Ltd	9,884
SEAPEAK NAPA	9254953	Bahamas	2003	Hudong-Zhonghua Shipbuilding	Seapeak LLC	Lauritzen Kosan A/S	9,875
INWANG	9240134	Korea, South	2003	Hudong-Zhonghua Shipbuilding	LX Pantos Co Ltd	STX Marine Service Co Ltd	8,299
LEONARDO B	9240146	Marshall Islands	2003	Hudong-Zhonghua Shipbuilding	William Hansen Invest AS	Transgas Shipping Lines SAC	8,300
LOTUS 6	9240158	Antigua & Barbuda	2003	Hudong-Zhonghua Shipbuilding	Unknown	HP Shipmanagement LLC	8,297

Vessel Name	IMO No.	Flag / Register	Build year	Builder	Owner	Manager/Operator	Cargo Capacity (m^3)
ORINDA	9240122	Turkey	2002	Hudong-Zhonghua Shipbuilding	Unknown	Orinda Denizcilik AS	8,292

Concept Designs of LCO_2 Carriers

As the prospects of LCO_2 transportation grows, a number of innovative conceptual designs and prospective projects have been developed for LCO_2 carriers. Some of the designs have received approval in principle from class societies and may progress to actual construction of the vessels in future.

Table 9.9 – Concept designs and prospective projects for LCO_2 carriers

Vessel / Project	Company	Date	Details
50,000 m^3 LCO_2 Carrier	MOL/ Mitsubishi Shipbuilding	Sept 2022	Approval in Principle (AiP) received for concept design
LCO_2 Carrier Fleet (20,000 – 85,000 m^3) & associated terminals	Ecolog	May 2022	EcoLog plans for a fleet of 60 specialized vessels along with an associated network of import and export terminals, to transport 50 million tons of CO_2 per year by 2035
Medium and Large Vessels	Mitsubishi Shipbuilding/ NYK Line/Class NK	May 2022	AiP received for joint development of CO_2 transport technology for LCO_2 carriers.
Large Scale Vessel	MOL	August 2022	AiP for design of a large-scale liquefied CO_2 carrier from ClassNK
30,000 m^3 LCO_2 Carrier	Capital Gas/LR/Liberia flag/Hyundai Mipo Dockyard	September 2022	LR and Liberia flag award design approval to HMD for the development of a LCO_2 carrier.
40,000 m^3 LCO_2 Carrier	Hyundai Heavy Industries	September 2022	AiP for design of a LP designed LCO_2 carrier provided with vertically arranged Bi-Lobe Type Tanks
30,000 m^3 LCO_2 Carrier	Equinor, Breeze Ship Design	November 2022	Plans to develop an NH_3 fuelled CO_2 carrier, for direct injection of CO_2 into permanent storage locations in the North Sea
40-70,000 m^3 & 20-30,000 m^3 LCO_2 Carrier	Hunter Group	March 2023	Hunter group intends to develop a low-pressure midstream shipping solution for CCS

Vessel / Project	Company	Date	Details
14,000 m^3 & 87,000 m^3 LCO_2 Carrier	PETRONAS, Mitsui O.S.K. Lines, Ltd. (MOL) and Shanghai Merchant Ship Design & Research Institute (SDARI)	June 2023	AiP received for short-haul LCO_2 carrier with the capacity of 14,000 m^3 and a long-haul LCO_2 carrier with the capacity of 87,000 m^3 with Dynamic Positioning System

9.5.2.2 Floating CO_2 Storage Units

FCSU are primarily in the conceptual stage at present. The design of these units is generally similar to large LCO_2 carrier, without propulsion system and will be constructed as per the requirements of IGC Code (same as described above for LCO_2 carrier). Because of the larger cargo tank size, the tanks are likely to be of low pressure bi-lobe type. Higher tensile stainless steel may be used for tank construction such as grade LT-FH 50 (or further material development).

As per concept 2 of this study, the LCO_2 receiving vessel may transfer the LCO_2 to FCSU at regular intervals. The FCSU is likely to be stationed at anchorage in sheltered waters of a port. Once the cargo tanks of the FCSU are full, it will be required to transfer the stored LCO_2 to a large LCO_2 carrier for long distance transportation. This section is focused on concept 2 FCSU which acts as an intermediate CO_2 storage unit where shore storage tanks may not be available. The concept 2 in this study considers a FCSU of 20,000 m^3 capacity. There is a possibility that the larger LCO_2 carriers being built may be put into FCSU service and when they are full, they would transport LCO_2 over long distance for sequestering or industrial use.

There is also possibility of FCSU-i. These will be stationed near depleted oil and gas fields offshore that have been earmarked as potential CO_2 storage sites. This study does not go into details of the injection capabilities of the FCSU-i.

At present only conceptual studies have been done as per table below.

Table 9.10 – Concept designs and prospective projects for LCO_2 carriers

Vessel / Project	Company	Date	Details
50,000 – 80,000 m^3 Floating CO_2 Storage	Altera / Hoegh LNG – Stella Maris Project	2021	Concept design of Carbon Capture, Storage and Offloading Unit (CCSO). Moored at jetty / quay or in sheltered area, size adaptable to need/site. Annual capacity 3 –7 mt/unit. Designed for shore power.
96,000 m^3 Floating CO_2 Storage	PETRONAS, Mitsui O.S.K. Lines, Ltd. (MOL) and Shanghai Merchant Ship Design & Research Institute (SDARI)	June 2023	AiP received for their jointly developed LCO_2 floating storage and offloading unit (FSO) for intermediate storage.

Vessel / Project	Company	Date	Details
100,000 m^3 Floating CO_2 Storage	MISC / SHI	August 2023	AiP received for innovative FCSU. The FCSU serves a dual role by functioning either as an intermediate CO_2 storage unit or, in tandem, as an injection vehicle (FCSU-i) for offshore CO_2 reservoirs.

9.5.3 Container Terminal

Limited modifications are required to container terminals (concept 4) to facilitate the offloading of LCO_2 in ISO tank containers. The ISO tank containers are a standard size, and so cranes at existing container terminals can lift them off container vessels onto waiting trucks.

It will be important to ensure intended container terminals have provision for a 'hazardous product zone' to suit the scale and rate of container transfer. While most container terminals already have designated hazardous product zones, it is likely that a zone specifically for LCO_2 offloading will be required, along with necessary safety procedures developed for the offloading and transporting of LCO_2 trucks within the port environment.

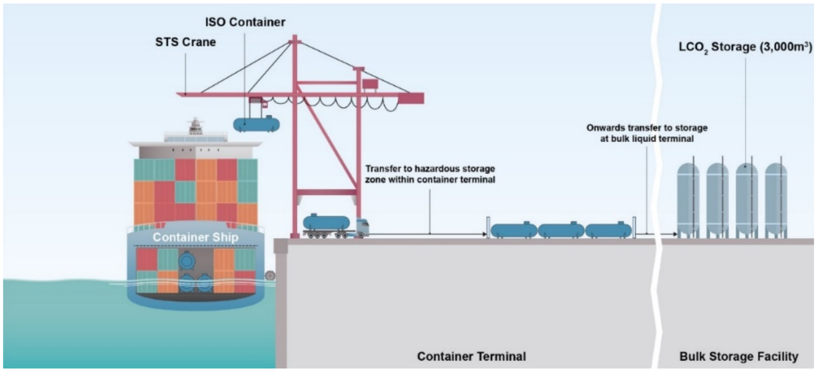


Figure 9.6 – Concept 4 -Ship-to-terminal with ISO tank containers

9.6 Technology Readiness of Offloading Assets

Technology readiness level (TRL) was developed by NASA to define the readiness of technologies for use in space flight. The EU has developed these definitions for applications to all technology, as shown in Table 9.11 below.

Table 9.11 – TRL definitions [19]

TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)

TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

Given that the scope of this study is from the onboard LCO_2 storage tank onwards, none of the equipment being used is novel. As shown in Figure 9.3, Figure 9.4 and Figure 9.6, the four concepts were designed using equipment that is used across existing LCO_2 or liquid gas industries. Used within their existing uses, the equipment proposed would have a high TRL of level 9. The equipment can be fabricated to form a new dedicated LCO_2 offloading system, though integration with other maritime infrastructure is possible and more likely (to achieve efficiency advantages). Concepts 1, 2 and 3 will use pipework and loading equipment of scale and specification seen in other applications. Tank storage capacities are within the boundaries of other operational processes. However, as the complete system for LCO_2 offloading has not yet formally been designed or applied in practice, the LCO_2 offloading system, as a whole, has a TRL between 1 and 2.

The fact that the equipment is used in other industries can accelerate the progress from TRL 1 to 9. Operations procedures for concepts 1-3 should be similar to those used for other bulk liquid transfer and for certain equipment, it may be just a case of getting the right certificates.

Concept 4 uses the least new infrastructure of the four concepts proposed in chapter 3, as it will use the existing cranes in container terminals. The key challenge for implementation will be developing procedures for port operations, especially if the scale of the loading is a significant portion of the port's other activities. Given that LCO_2 is being transported in ISO tank containers in the present day, this concept will likely be TRL 9.

9.7 References

[1] Borg CO2, "CO_2 terminal for Borg CO_2," [Online]. Available: https://issuu.com/ncce.no/docs/sluttrapport_borg_co2_side_for_side/s/12611076.

[2] E. Turney, Interviewee, *Phonecall with Nippon Gases to discuss LCO_2 infrastructure.* [Interview]. August 2023.

[3] BBC, "Warrenpoint Port set for £9.5m carbon dioxide terminal," 2019. [Online]. Available: https://www.bbc.co.uk/news/uk-northern-ireland-48338943.

[4] London Container Terminal, "London Container Terminal Operations," 2023. [Online]. Available: https://www.londoncontainerterminal.com/services/operations/.

[5] Yara, "New liquid CO_2 ship for Yara," 2015. [Online]. Available: https://www.yara.com/news-and-media/news/archive/2015/new-liquid-co2-ship-for-yara/.

[6] CO_2Meter, "Carbon Dioxide (CO_2) Purity Grade Chart," 2022. [Online]. Available: https://www.co2meter.com/en-uk/blogs/news/co2-purity-grade-charts.

[7] Linde Engineering, “CO_2 purification and liquefaction plants,” [Online]. Available: https://www.linde-engineering.com/en/process-plants/co2-plants/co2-purification-and-liquefaction/index.html. [Accessed 2023].

[8] Bremen Ports, “INNOVATIVE INITIATIVE FOR GREENHOUSE GAS REDUCTION,” 2022. [Online]. Available: https://www.bremenports.de/en/press/innovative-initiative-for-greenhouse-gas-reduction.

[9] European Commission, “Poland – EU CCS Interconnector,” 2023. [Online]. Available: https://ec.europa.eu/energy/maps/pci_fiches/PciFiche_12.9.pdf.

[10] Offshore Energy, “First temporary CO_2 storage tank placed for Northern Lights CCS project,” 2023. [Online]. Available: https://www.offshore-energy.biz/first-temporary-co2-storage-tank-placed-for-northern-lights-ccs-project/.

[11] WPSP, “Port of Gothenburg - CifraCap Carbon Infrastructure Capture,” 2020. [Online]. Available: https://sustainableworldports.org/project/port-of-gothenburg-cinfracap-carbon-infrastructure-capture/.

[12] CCSA, “LinkedIn Post - 7 CO_2,” 2023. [Online]. Available: https://www.linkedin.com/posts/carbon-capture-and-storage-association_netzero-ccus-carboncapture-activity-7097547096903270400-rdQC/?utm_source=share&utm_medium=member_desktop.

[13] Carbfix, “Coda Terminal,” 2023. [Online]. Available: https://www.carbfix.com/codaterminal.

[14] Ship Technology, “UK’s Immingham port to get new CO_2 import terminal,” 2022. [Online]. Available: https://www.ship-technology.com/news/immingham-port-co2-import-terminal/?cf-view&cf-closed.

[15] Project Aramis, “Project Overview,” 2023. [Online]. Available: https://www.aramis-ccs.com/project.

[16] “https://co2next.nl/,” [Online].

[17] “https://koole.com/horisont-energi-and-koole-terminals-are-discussing-a-potential-cooperation-developing-the-midstream-part-of-the-planned-european-ccs-value-chain/,” [Online].

[18] IGC Code - International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, 2014.

[19] European Commission, “Technology Readiness Levels,” 2014. [Online]. Available: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

[20] Project Aramis, “CO_2 SPECIFICATIONS FOR ARAMIS TRANSPORT INFRASTRUCTURE,” 2023. [Online]. Available: https://www.aramis-ccs.com/files/ARM-CPT-BB8-PRO-MEM-0033-rev-6.2-public-version-NEW.pdf.

10. CAPEX and OPEX Model for Cost Estimation for Infrastructure

10.1 Methodology

A visual representation of the boundary of the estimate is shown in Figure 10.1 below.

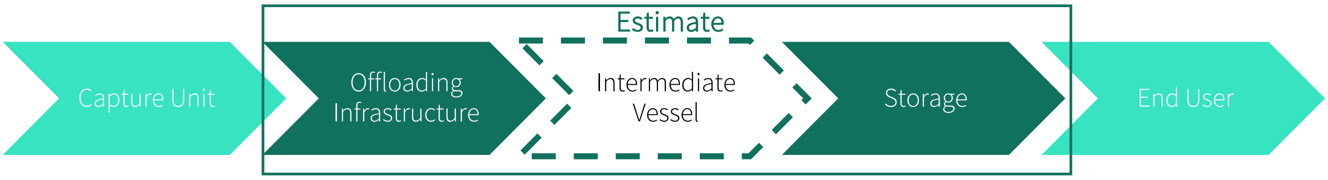


Figure 10.1 – Boundary of estimate

Furthermore, a generic set of exclusions was used to create an estimating boundary:

- Forward price escalation from the estimate base date
- Owners' costs (including project management team, owner's consultants such as environmental, geotechnical, marine etc., owner's facilities and services, owner's commissioning & operations team, construction and commissioning management)
- Local planning and fees
- Security (no allowance for personnel security at site, transit from camp, meet and greet)
- Operation and maintenance spares (aside from first two years' operating spares)
- Offshore logistics (flotel or other temporary accommodation (e.g., Accommodation Support Vessel (ASV) / Temporary Living Quarters (TLQ)), helicopter transport, supply vessels, standby and rescue vessels, crew boats and onshore marine support base)
- Quarantine costs
- Non-typical airfreight of materials due to schedule issues or late availability
- Environmental consultants and permit costs
- Authority approvals / permit costs
- Cost of land / seabed leasing costs
- Currency fluctuations / risk
- All survey costs, including but not limited to: geotechnical, bathymetric, meteorological, oceanographic, and environmental surveys and studies
- Taxes including: import tax; customs duties; value added tax; investment tax; local tax; sales tax; withholding tax and other financial charges or levies
- Purchase of first fill feedstocks (diesel, gas, and condensate) for onshore and offshore commissioning

- Marine certification and marine warranty surveyor services
- Any required seabed ground improvements below foundation bed
- Operator and maintenance training
- Start-up costs (pre-ops)
- Operation of facility after handover assistance to Owner
- Decommissioning and final removal of facilities

10.1.1 CAPEX

This part of the report describes the development of cost models to produce a Class 5 estimate for each of the concepts discussed in chapter 3. To produce the CAPEX estimates, ACCE (Aspen Capital Cost Estimator) was used. ACCE uses a database of capital projects to generate estimates for projects by sizing and costing equipment from analogues.

Using the PFD created for each concept, a preliminary equipment list was built, and populated with key equipment. Using the assumption of 250m^3/hr flow rate as a starting point based on 8 hours offloading time, basic calculations were carried out to provide ACCE with the required information for the software to size the equipment. From the start of the concept development, a list of estimating assumptions and justifications was created to support the results from ACCE. The list of estimating assumptions can be seen in Table 10.1 below.

The Q1 2022 cost basis used in ACCE has different factors of costs for each of the possible locations These are shown in Figure 10.2 below. Given that we have not yet identified a location for the LCO_2 offloading, the default location (USA) is chosen and costs can be modified in a future phase of the study.

Cost Basis: First Quarter 2022

	Material	Construction	Engineering	Construction Management
USA	3230	2410	1490	1980
UK	4140	6090	5860	5920
EU	3100	2260	2320	2160
JAPAN	2140	1740	2390	2230
ME	3150	3570	1620	2920

Figure 10.2 – ACCE cost basis

Table 10.1 – CAPEX assumptions

Equipment Item	Assumption	Justification	Concept
General	40 hour working week	Default ACCE assumption	All
General	One main substation and auxiliary electrical / instrument equipment is included per concept	Default ACCE assumption	All

Equipment Item	Assumption	Justification	Concept
General	One main control system is included in estimate per concept	Default ACCE assumption, Integrated process control system is expected at this stage	All
General	Additional Equipment design allowance is included as 7% of equipment cost	Default ACCE assumption	All
General	No escalation is included in costing	Costs are based on if the project were to start straight away using the most recent ACCE cost basis. Scheduling for each concept was not included in project scope therefore accurate durations to execute each concept are not available	All
General	25% contingency is applied to all contract costs in ACCE	This is due to the limited information available at this stage of the project	All
General	Offloading flow rate from onboard ship LCO_2 tank is $250m^3/hr$	An upper limit of eight hours offloading time is required, combined with a maximum offloading capacity of $2,000m^3$, meaning that $250m^3/hr$ will be sufficient flow	All
General	All rotating equipment will have 1 spare unit	To minimise downtime for maintenance during normal operation. Spare units will be installed in the system using "SPAR" installation option in ACCE, which allows for less installation bulks than a single installed unit to account for the fact that the two units would be installed in the same system	All
General	Basic site civils will be costed including chain link fence, gate and floodlighting	Onshore site locations will require this to allow new infrastructure and equipment to be installed	1; 3; 4
General	Buildings are included for control system and workshop	It is likely that these would be required at site to house control equipment and to perform routine maintenance	1; 3; 4
LCO_2 Storage Tank Onboard Ship	Tank will operate at MP conditions	Base case was selected as MP.	1; 2; 3;

Equipment Item	Assumption	Justification	Concept
Offloading Pump	Pump is deepwell (with motor sitting on top of tank) or submerged type.	Pump could be deepwell type (with motor sitting on top of tank) or submerged type. This configuration is standard in marine liquid transfer operations such as LPG. It is expected that LCO_2 tank will have submerged pump.	1; 2; 3;
PBU	Unit will operate using ambient air as the heating medium	This configuration is used in LNG operations and will minimise systems requirement onboard ship	1; 2; 3;
PBU	Unit will be modelled as a simple shell & tube heat exchanger in ACCE	ACCE does not contain a suitable exchanger to model the type of ambient air vaporiser commonly seen for PBU's. To avoid overdesign and over costing for this unit, a simple exchanger is sufficient.	1; 2; 3;
PBU	Operating temperature will be -35 °C to -18 °C	-18 °C will ensure complete vaporisation of CO_2 based on range of operating pressures, but remains close to vapor phase envelope to ensure minimum duty on exchanger	1; 2; 3;
LCO_2 Receiving Vessel Tanks	Offloading flow rate from intermediate ship LCO_2 tank is 935 to 940m^3/hr	Based on eight hours offloading duration for 7,500m^3 total storage capacity	2; 3
Vaporiser KO Drum	Vessel is sized on a basis of three minutes' residence time	This is a sufficient volume to allow safe operation given that the stream will be completely vaporised	1; 2; 3;
Booster Pumps	10 bar DP in booster pumps	The booster pumps may not be required for normal operation, however 10 bar DP is sufficient given the range of operating pressure	All
Vapor Header	200m length of header	Conservative estimate of length	1; 2; 3;
LCO_2 ISO Tank Container	Cost of purchasing 16 No. ISO tank containers will be included	16 No. 20ft containers will be required to meet 300m^3 LCO_2 offloading envelope for this concept, given the working volume of 19m^3 per container	4
LCO_2 ISO Tank Container	LCO_2 ISO tank container is modelled as a horizontal storage tank using quoted equipment cost of $145,000. This cost includes instrumentation, offloading pump and two flanged flexible hoses per unit.	Quoted cost from ASCO, a well-known LCO_2 ISO tank container vendor	4

Equipment Item	Assumption	Justification	Concept
General	ISO tank container trucks and cranes will not be dedicated assets	It is reasonable to assume that port locations will have available trucks and cranes to move LCO_2 ISO tank containers with an associated service fee, and new dedicated trucks and cranes will not need to be purchased	4
General	Forecourt parking lot area of 760m^3 allowed for ISO tank container trucks	This additional area will be required for concept 4 to allow trucks to access tanks	4
General	To allow for pump housing, loading arm and vaporiser system, 26m x 26m area is allowed at site	Estimation based on equipment sizing with allowance for cabins	1; 3; 4
Liquid Bulk Terminal Storage Tank	4,200m^2 is allowed for tank area in concepts 1 and 3. 1,200m^2 is allowed for tank area in concept 4	The tanks will have spacing equal to 100% of the diameter of each tank. Sufficient spacing is required to allow ease of access for maintenance	1; 3;
General	Shore pipeline must be made of stainless steel	To withstand carbonic acid which may form in the upstream systems due to any free water present	All
LCO_2 Receiving Vessel	The cost of purchasing a vessel must be considered	Both brand new and pre-owned options will be explored, with cost options available for either option, or neither	2; 3
Floating Storage Vessel	The cost of purchasing a vessel must be considered	Brand new option will be explored, as pre-owned not available	2
Floating Storage Vessel	Vessel will be located at anchorage	Additional equipment for stabilisation is not required	2
Floating Storage Vessel	The offloading & booster pumps and refrigeration unit onboard the FCSU are included in FCSU cost.	The vessel is typically designed as a single unit.	2
General	StS transfer will take place in a sheltered area	Additional equipment for stabilisation is not required	2
General	A cost factor of 1.4 will be applied to marine or offshore equipment, with a cost factor of 1.6 applied to installation costs.	ACCE uses a database of onshore facilities. Factor is based on increased complexity of marine & offshore activity and more specialised personnel required	All

Equipment Item	Assumption	Justification	Concept
General	For offshore equipment, the area type "EXOPEN" will be selected.	This refers to existing open steel structure. It is assumed that the additional costs for mounting and supporting marine/offshore equipment will be absorbed by the additional cost/installation factors applied	1; 2; 3
Intermediate Refrigeration Unit	ACCE refrigeration unit is used with the minimum duty, 180kW, and condenser temperature of -40 °C	Given the heat flow from the environment is calculated based on a max case Boil-off Rate of 0.5%/day, this duty is oversized. However given the limited amount of information on this unit and its operation on the intermediate LCO_2 vessel, this gives allowance for extra complexity.	2; 3
Loading Arm	€1,188,000 is allowed for the smaller loading arm (ship-to-intermediate vessel or shore transfer), and €1,255,000 is allowed for the larger loading arm (IRV to FCSU or Shore transfer)	Based on in house historical data.	1; 2; 3
Vapor Return Compressor & Spare	This unit is sized based on 185 to 195m^3/hr capacity	Given that this compressor is to supplement the vapor header rather than for the full flow to pass through it, it is not required for a full-sized compressor to be included.	1; 2; 3
Intermediate Vapor Return Compressor & Spare	This unit is sized based on 50m^3/hr capacity	Given that this compressor is to supplement the vapor header rather than for the full flow to pass through it, it is not required for a full-sized compressor to be included.	2; 3
Intermediate Offloading Pump	Where there is an intermediate LCO_2 ship, the offloading pumps will have a smaller fluid head, which will be supplemented by the booster pumps	There is a max flow rate and fluid head limit associated with submerged pumps of this type, which would be exceeded if the head on these pumps were not reduced	2; 3

10.1.2 OPEX

Given the early development of LCO_2 offloading operations, the OPEX costs are based on the high-level assumptions outlined in Table 10.2, below. The scope of the OPEX estimation is the same as for the CAPEX costs in Section 10.1.1, not accounting for costs associated with capture or liquefaction of CO_2. The operation will begin with the vessel safely moored, ready to offload and finish with an empty tank and offloading hoses disconnected and purged.

Table 10.2 – OPEX assumptions

Assumption	Justification	Concept
No additional dedicated crew for offloading operations will be required on the vessel where CO_2 is captured and liquefied	It will be in the interests of the ship owners to keep crew numbers to minimum required, therefore it is unlikely there would be crew specifically for offloading only	1; 2; 3
15-18 crew members will be required for the intermediate LCO_2 ship, therefore 18 will be included in OPEX costs	Based on numbers for LPG and NH_3 ships of similar capacity	2; 3
22 crew members will be required for FCSU.	Based on numbers for LNG and NH_3 ships of similar capacity	2
$170k is allowed per year for trucking services	Glassdoor estimated pay for a Yard Driver at Boasso Global (ISO tank container services company) is $56,768 per year. Approx 3 times this cost will be allowed to include other service-related charges	4
CO_2 will be used as the purge gas for the process	This is a suitable purge gas that will simplify the utility systems required	All

Using these assumptions, approximate % splits of OPEX costs in similar reference projects from Arup's internal cost database were applied to the direct field costs of the CAPEX to generate estimates for onshore operations costs. These estimations were made based on in house data for approximate percentages of OPEX as a proportion of CAPEX for onshore facilities.

10.2 Results

This section shows the outcome of the cost estimating calculations following the methodologies outlined in Section 10.1. The base case total CAPEX for each concept is shown in Table 10.3 below, with a more detailed breakdown in the subsection relating to each concept.

Table 10.3 – CAPEX summary

	Base Case (Million USD)	Alternative Case (Million USD)
Concept 1- Ship-to-liquid bulk terminal	$166	-
Concept 2- Ship-to-FCSU with intermediate LCO_2 receiving vessel	$178	$141
Concept 3 – Ship-to-bulk liquid terminal with intermediate LCO_2 receiving vessel	$244	$207
Concept 4 – Ship-to-terminal with ISO tank containers	$33	-

Note – The details of ship costs and shore costs are available in Section 10.2.1.

For the base case of these estimates, concepts 2 & 3 are costed on the basis of a new intermediate LCO_2 carrier being purchased. There is also the possibility that an existing carrier could be purchased and re-purposed at a price of $15m compared to the $52m figure used for purchasing a new carrier which is used in the alternative case. The impact on cost for these concepts is shown in the alternative case column of Table 10.3 above. The FCSU cost is considered as new building cost for both base and alternative case as there are no existing vessels suitable to act as FCSU.

10.2.1 CAPEX

10.2.1.1 Concept 1 - Ship-to-Liquid Bulk Terminal

Table 10.4 – Concept 1 CAPEX summary

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
SHORE	LCO_2 Storage Tanks (20 x 1000m^3)	1,639,429	85,556,000	87,195,429
	Shore Loading Arm	10,287	1,250,000	1,260,287
	Vapor Return Compressor	7,646	503,100	510,746
	Vapor Return Compressor S	7,646	503,100	510,746
	Vaporiser Heater Elec	1,580	28,800	30,380
	Vaporiser Booster Pump	465	7,900	8,365
	Vaporiser Booster Pump S	465	7,900	8,365
	Vaporiser KO Drum	910	37,000	37,910
	Shore Subtotal			89,562,228
SHIP	Booster Pump	4,313	47,400	51,713
	Booster Pump S	4,313	47,400	51,713
	Offloading Pump	3,808	53,500	57,308
	Offloading Pump S	3,808	53,500	57,308
	PBU	3,827	36,700	40,527
	Ship Subtotal			258,569
	Additional Design Allowance		6,167,700	6,167,700
	Total Equipment Costs	1,688,497	94,300,000	95,988,496
	(2) Equipment	1,688,497	94,300,000	95,988,496
	(3) Piping	905,379	3,209,991	4,115,370
	(4) Civil	807,375	1,099,823	1,907,199
	(5) Steel	203,703	1,749,809	1,953,511
	(6) Instruments	177,636	1,428,518	1,606,154
	(7) Electrical	284,468	1,208,085	1,492,553
	(8) Insulation	2,708,404	3,333,143	6,041,547

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	(9) Paint	193,336	148,343	341,679
	Total Direct Field Costs	**6,968,798**	**106,477,712**	**113,446,510**
	Field Const Supv			2,309,801
	Start-up, Commissioning			194,600
	Fringe Benefits			1,463,400
	Burdens			1,672,500
	Consumables, Small Tools			209,100
	Misc (Insurance, Etc)			526,100
	Scaffolding			209,100
	Equipment Rental			1,952,900
	Field Services			541,500
	Temp Const, Utilities			118,400
	Indirect Field Costs			**9,197,401**
	Freight			
	Taxes and Permits			
	Engineering and HO			2,298,200
	Home Office Const Suppt			415,500
	G and A Overheads			3,679,318
	Contract Fee			3,421,939
	Contingency			33,114,718
	Total Non-Field Costs			**42,929,675**
	Project Total Costs			**165,573,586**

10.2.1.2 Concept 2 - Ship-to-Floating CO_2 Storage with Intermediate LCO_2 Receiving Vessel

Note that dark grey rows for equipment on FCSU and IRV are included within vessel cost.

Table 10.5 – Concept 2 CAPEX summary

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
FCSU	FCSU Loading Arm	16,459	1,320,000	1,336,459
	Vapour Return Compressor	14,558	935,900	950,458

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	Vapour Return Compressor S	14,558	935,900	950,458
	Vaporiser Heater Elec	8,425	135,000	143,425
	Vaporiser Booster Pump	1,855	18,700	20,555
	Vaporiser Booster Pump S	1,855	18,700	20,555
	Vaporiser KO Drum	1,518	93,100	94,618
	FCSU Subtotal			**3,516,528**
SHIP	Booster Pump	4,313	47,600	51,913
	Booster Pump S	4,313	47,600	51,913
	Offloading Pump	3,808	53,500	57,308
	Offloading Pump S	3,808	53,500	57,308
	PBU	3,827	36,700	40,527
	Ship Subtotal			**258,969**
IRV	PBU	6,659	147,600	154,259
	Offloading Pump	6,706	208,800	215,506
	Offloading Pump S	6,706	208,800	215,506
	Booster Pump	8,887	208,800	205,087
	Booster Pump S	8,887	208,800	205,087
	Loading Arm	16,459	1,250,000	1,266,459
	Refrigeration	11,500	298,000	309,500
	Vapor Return Compressor	12,234	704,400	716,634
	Vapor Return Compressor S	12,234	704,400	716,634
	Vaporiser Heater Elec	2,528	40,500	43,028
	Vaporiser Booster Pump	744	11,100	11,844
	Vaporiser Booster Pump S	744	11,100	11,844
	Vaporiser KO Drum	1,457	48,800	50,257
	IRV Subtotal			**4,142,482**
	Additional Design Allowance		640,500	644,861
	Total Equipment Costs	**1,041**	**2,199,400**	**2,240,289**
	(2) Equipment	1,041	2,199,400	2,240,289
	(3) Piping	230,952	627,719	858,672
	(4) Civil	83,523	105,418	188,942
	(5) Steel	8,978	45,427	54,405

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	(6) Instruments	70,050	364,237	434,287
	(7) Electrical	302,347	1,936,999	2,239,346
	(8) Insulation	88,714	126,168	214,882
	(9) Paint	23,746	14,290	38,037
	(10) IRV			52,000,000
	(11) FCSU			68,000,000
	Total Direct Field Costs	809,352	5,419,659	126,268,858
	Field Const Supv			407,400
	Start-up, Commissioning			48,600
	Fringe Benefits			206,500
	Burdens			236,000
	Consumables, Small Tools			29,500
	Misc (Insurance, Etc)			74,200
	Scaffolding			29,500
	Equipment Rental			155,000
	Field Services			70,300
	Temp Const, Utilities			15,500
	Indirect Field Costs			1,272,500
	Freight			
	Taxes and Permits			
	Engineering and HO			6,204,201
	Home Office Const Suppt			66,400
	G and A Overheads			4,018,017
	Contract Fee			3,203,862
	Contingency			36,856,596
	Total Non-Field Costs			50,349,076
	Project Total Costs			177,890,435

10.2.1.3 Concept 3 - Ship-to-Liquid Bulk Terminal with Intermediate LCO_2 Receiving Vessel

Note that dark grey rows for equipment on IRV are included within vessel cost.

Table 10.6 – Concept 3 CAPEX summary

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
SHORE	LCO_2 Storage Tanks (20 x 1000m^3)	1,639,429	85,556,000	87,195,429
	Shore Loading Arm	6,358	1,320,000	1,326,358
	Vapor Return Compressor	9,099	668,500	677,599
	Vapor Return Compressor S	9,099	668,500	677,599
	Vaporiser Heater Elec	5,266	96,000	101,266
	Vaporiser Booster Pump	1,159	13,300	14,459
	Vaporiser Booster Pump S	1,159	13,300	14,459
	Vaporiser KO Drum	910	98,000	98,910
	Shore Subtotal			90,075,418
SHIP	Booster Pump	4,313	47,600	51,913
	Booster Pump S	4,313	47,600	51,913
	Offloading Pump	3,808	53,500	57,308
	Offloading Pump S	3,808	53,500	57,308
	PBU	3,827	36,700	40,527
	Ship Subtotal			258,969
IRV	PBU	6,659	147,600	154,259
	Offloading Pump	6,706	208,800	215,506
	Offloading Pump S	6,706	208,800	215,506
	Booster Pump	8,887	208,800	205,087
	Booster Pump S	8,887	208,800	205,087
	Loading Arm	10,173	1,250,000	1,260,173
	Refrigeration	11,500	298,000	309,500
	Vapor Return Compressor	1,006,700	1,006,700	1,021,909
	Vapor Return Compressor S	1,006,700	1,006,700	1,021,909
	Vaporiser Heater Elec	2,528	40,500	43,028
	Vaporiser Booster Pump	744	11,100	11,844
	Vaporiser Booster Pump S	744	11,100	11,844
	Vaporiser KO Drum	1,457	63,700	65,157
	IRV Subtotal			4,115,358

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	Additional Design Allowance		6,573,700	6,583,912
	Total Equipment Costs	**1,692,586**	**95,155,712**	**96,918,299**
	(2) Equipment	1,692,586	95,155,712	96,918,299
	(3) Piping	1,039,859	3,638,594	4,678,453
	(4) Civil	858,871	1,166,031	2,024,902
	(5) Steel	205,962	1,761,929	1,967,891
	(6) Instruments	216,396	1,544,694	1,761,090
	(7) Electrical	426,841	2,488,166	2,915,006
	(8) Insulation	2,754,040	3,395,510	6,149,550
	(9) Paint	205,413	155,438	360,851
	(10) IRV			51,999,996
	Total Direct Field Costs	**7,399,968**	**109,306,074**	**168,776,039**
	Field Const Supv			2,488,501
	Start-up, Commissioning			214,900
	Fringe Benefits			1,574,900
	Burdens			1,799,900
	Consumables, Small Tools			225,000
	Misc (Insurance, Etc)			566,200
	Scaffolding			225,000
	Equipment Rental			2,011,100
	Field Services			579,200
	Temp Const, Utilities			126,600
	Indirect Field Costs			**9,811,301**
	Freight			
	Taxes and Permits			
	Engineering and HO			5,127,201
	Home Office Const Suppt			450,700
	G and A Overheads			5,481,080
	Contract Fee			4,792,538
	Contingency			49,638,556

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	Total Non-Field Costs			65,490,075
	Offloading Total Costs			244,077,415

10.2.1.4 Concept 4 - Ship-to-Terminal with ISO Tank Containers

Table 10.7 – Concept 4 CAPEX summary

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
SHORE	LCO_2 Storage Tanks (3 x 1000m^3)	245,914	12,833,400	13,079,314
	Booster Pump	2,310	29,700	32,010
	Booster Pump S	2,310	29,700	32,010
	Shore Subtotal			**12,892,800**
	LCO_2 ISO tank containers (16 Nos)	32,256	2,320,000	2,352,256
	Additional Design Allowance		906,800	906,800
	Total Equipment Costs	**282,791**	**16,119,600**	**16,402,391**
	(2) Equipment	282,791	16,119,600	16,402,391
	(3) Piping	433,641	519,021	952,662
	(4) Civil	337,530	495,536	833,066
	(5) Steel	30,279	260,380	290,659
	(6) Instruments	110,123	404,540	514,663
	(7) Electrical	136,645	671,326	807,972
	(8) Insulation	403,440	492,397	895,837
	(9) Paint	27,823	21,391	49,214
	Total Direct Field Costs	**1,762,272**	**18,984,191**	**20,746,463**
	Field Const Supv			734,900
	Start-up, Commissioning			73,000
	Fringe Benefits			370,100
	Burdens			422,900

	Account	Labor Cost (USD)	Matl Cost (USD)	Total Cost (USD)
	Consumables, Small Tools			52,900
	Misc (Insurance, Etc)			133,100
	Scaffolding			52,900
	Equipment Rental			496,400
	Field Services			132,000
	Temp Const, Utilities			29,000
	Indirect Field Costs			2,497,200
	Freight			
	Taxes and Permits			
	Engineering and HO			1,291,900
	Home Office Const Suppt			145,200
	G and A Overheads			697,310
	Contract Fee			852,863
	Contingency			6,557,734
	Total Non-Field Costs			9,545,007
	Project Total Costs			32,788,670

10.2.2 OPEX

This section shows the outcome of the cost estimating calculations following the methodologies outlined in Section 10.1.2 . The base case total OPEX for each concept is shown in Table 10.8 below, with a more detailed breakdown in the subsection relating to each concept.

Table 10.8 – OPEX summary

	Annual Operations Cost (Million USD)
Concept 1- Ship-to-liquid bulk terminal	5.5
Concept 2- Ship-to-FCSU with intermediate LCO_2 receiving vessel	11.4
Concept 3 – Ship-to-shore terminal with intermediate LCO_2 receiving vessel	10.3
Concept 4 – Ship-to-terminal with ISO tank containers	1.0

10.2.2.1 Offshore

Operations and maintenance expenses for the IRV and FCSU have been estimated. The cost values include a weighting for crew, union contributions, training, welfare, recruitment, victualling and other allowances. This also includes the cost of repatriation of crew to their home time on a six-week on, six-week off crew rotation. The categories included in cost are summarised below:

- Insurance – hull & machinery, protection & indemnity
- Technical – stores & consumables, spares, lubricants & oils
- Management fees
- Dry docking – each vessel will enter a dry dock once every five years for a 14-day period
- Others – administration, port expenses, logistics

Table 10.9 – Offshore operational and maintenance base costs per IRV/FCSU per year

Cost	IRV (Million USD)	FCSU (Million USD)
Crew	3.46	3.85
Insurance	0.21	0.46
Technical	0.69	1.50
Other expenses	0.20	0.44
Management fee	0.18	0.39
Total Operational Expense (excluding fuel)	4.74	6.64

10.2.2.2 Onshore

For the onshore costs of concepts 1 & 3, direct costs for the shore facilities are taken from concept 1, which represents only the shore facility, and rounded to a value of $120m. For concept 4, a rounded direct cost of $25m is used. The values are shown in Table 10.10 below for the onshore operations costs of concepts 1, 3 & 4.

Table 10.10 – Onshore bulk liquid storage operational costs per year

Cost	Concept 1 & 3 (Million USD)	Concept 4 (Million USD)
Operations	2.34	0.43
Maintenance	1.08	0.20
Engineering and Technical	1.59	0.29
Insurance	0.53	0.10
Total Operational Expense	5.54	1.02

11. Ranking the Operability of Concepts

11.1 Methodology

The ranking analysis is divided into a comparison of the different forms of LCO_2 and how it will be impacted by each offloading concept; and a multi-criteria assessment of each offloading concept that results in a ranking of the concepts by their operability.

11.2 End Use Applicability

Potential end users of captured CO_2 were considered based on perceived existing demand and scale. The end users which were considered are as follows:

- Sequestration – >95% CO_2 purity [1]
- Feedstock for synthetic fuels production – >95% CO_2 purity
- Medical use – >99.5% CO_2 purity [2]
- Food/beverage – >99.9% CO_2 purity [3]

The following end users were excluded:

- Carbonation & concrete curing – not considered due to low likelihood of uptake in construction industry [4]
- Research – small quantities expected to be required resulting in low income generation

It should be noted that securing an end use does not necessarily relate to effective decarbonisation. There is still considerable CO_2 retained in the atmosphere for all uses other than sequestration and all uses are at risk to leaks or carbon emitting processing equipment. The effectiveness of decarbonisation for any onboard carbon operation implemented should be thoroughly assessed across the value chain during the development stage.

11.3 Results for End Use Applicability

The results for the CO_2 end use applicability analysis are displayed in Table 11.1 below. Concepts 1, 2 and 3 are grouped together as they will be offloaded using similar infrastructure and similarly sized offloading envelopes. The four concepts are as follows:

Concept 1 – Ship-to-liquid bulk terminal

Concept 2 – Ship-to-floating CO_2 storage with intermediate LCO_2 receiving vessel

Concept 3 – Ship-to-liquid bulk terminal with intermediate LCO_2 receiving vessel

Concept 4 – Ship-to-terminal with ISO tank containers

Table 11.1 – Captured CO_2 end users

CO_2 End User	Concepts 1/2/3	Concept 4
Sequestration >95%	Based on the Project Aramis specification [1] of LCO_2, the lower % purity required will increase the simplicity of purification of captured CO_2. The large offloading envelopes of concepts 1/2/3 are well suited to sequestration given that the projects that are currently planning CO_2 storage are in the scale of megatons. Given that sequestration permanently stores large quantities of CO_2 below the ground and therefore removes carbon from the atmosphere, this has the greatest environmental benefit of any of the end users. These projects are unlikely to feature their own sequestration facilities, this is likely to be a service that comes at a cost. This may mean that storing large quantities of CO_2 becomes very expensive.	Following the Project Aramis specification [1] of CO_2 as in concepts 1/2/3, this will have a benefit when CO_2 is being captured from a variety of sources, which would probably be more likely when the size of each delivery is smaller, compared to the ship-based transfer. Sequestration may be better suited to larger delivery envelopes such as those in concepts 1/2/3, given that it has the capability to store large quantities of CO_2. Similar to concepts 1/2/3 the service costs of sequestration must be considered, which may be beneficial for the ISO tank container concept as this will be dealing with smaller quantities of CO_2.
Feedstock for Synthetic Fuel Production >95%	As with sequestration, the lower % purity required will increase the simplicity of purification of captured CO_2. This technology can help reduce growth in CO_2 emissions but not necessarily reduce emissions overall due to the retained CO_2 in the atmosphere.	The ISO tank container concept is likely to have a disadvantage for synthetic fuel production compared to the other concepts given the smaller quantities of delivery. For the manufacturing of the fuels to be efficient, they are likely to have to operate at large scale.
Medical Use >99.5%	The larger size Linde medical CO_2 cylinder contains 9.0 kg of CO_2 at 50 bar [2]. Providing there was a sufficient demand from the medical industry, there would be a large cost of purifying, compressing and bottling the CO_2 for medical use. Further investigation into the demand for medical grade CO_2 would be required to determine whether this is viable. From an environmental perspective, it is highly unlikely that CO_2 used in a medical environment will be captured again and is therefore likely to be released back into the environment.	Compared with concepts 1/2/3, given the smaller offloading envelopes in the ISO tank container concept, this would require a smaller-scale purification and compression facility. If there was insufficient demand to produce medical grade CO_2 in the quantities of concept 1/2/3, this may make concept 4 a more attractive option.

CO_2 End User	Concepts 1/2/3	Concept 4
Food/Beverage >99.9%	Similar to in medical use, there will be a large cost purifying the CO_2 captured to a suitable grade, where it will ultimately end up being re-released to the atmosphere.	As in medical use, there would be a lower CAPEX cost for the infrastructure required to purify smaller deliveries of CO_2. The ISO tank container suits higher purity requirements better due to the isolated containment and control over mixing.

11.4 Operability Ranking

To rank the operability of the offloading concepts, each have been assessed against four categories and given a score in each category of 1-5, relative to each other rather than absolute values. Each concept also has a weighting factor applied to the score before they are added together. This will result in each concept being given a total score out of 35 points, which will allow the operability of the concepts to be ranked quantitatively.

- Impact on Host Vessel's Operations – the extent to which the LCO_2 offloading will impact the ships' ability to perform its normal cargo functions
- Scalability – the ability of the concept to perform at the scale of commercial operation that would be expected in industry
- Costs – The CAPEX/OPEX of the concept
- Ease of operation – the complexity of the process such as the number of offloads and required equipment to maintain process conditions
- Safety – the risks associated with operation and maintenance of the concept
- Technology readiness – the TRL level for the concept as discussed in section 9.6 of this report

It should be noted that the criteria is designed to favour scalable solutions for the mid-term which is why the scalability criteria has a weighting of two.

11.5 Results for Operability Ranking

The results for the multi-criteria operability assessment are displayed in Table 11.2 below.

Table 11.2 – Multi-criteria operability assessment of LCO_2 offloading concepts

Assessment Criteria	Concept 1		Concept 2		Concept 3		Concept 4	
Impact on Host Vessel's Operations Score Weighting = 1.0	2	• The vessel hosting carbon capture equipment may be negatively impacted by the necessity to perform LCO_2 offloading operations. • This concept would heavily rely on port availability which would also impact normal operations.	5	• The vessel hosting carbon capture equipment may be negatively impacted by the necessity to perform LCO_2 offloading operations. This may be mitigated to some extent by the use of the intermediate vessel which would be a dedicated asset for transporting LCO_2. • The intermediate vessel would allow offloading to take place with more flexibility when the tank is fuller. This would help to avoid scenarios where a half empty tanker was offloaded and therefore reduce the impact on normal vessel operations. • The reduced reliance on port availability compared to other concepts due to the use of intermediate ship would reduce the impact on the host operations.	5	• The vessel hosting carbon capture equipment may be negatively impacted by the necessity to perform LCO_2 offloading operations. This may be mitigated to some extent by the use of the intermediate vessel which would be a dedicated asset for transporting LCO_2. • The intermediate vessel would allow offloading to take place with more flexibility when the tank was fuller. This would help to avoid scenarios where a half empty tanker was offloaded and therefore reduce the impact on normal vessel operations. • This concept would have slightly reduced reliance on ports compared to concept 1 due to the use of an intermediate vessel.	3	• The time taken by the ISO tank container crane would reduce the efficiency offloading other revenue generating containers and a reduced capacity. Likewise with the space taken up by the container. • It is expected to have 10-15 LCO_2 tanks to be fully filled before carrying out the next tank swapping which will reduce the carrying capacity of the ISO tank container ship
Scalability Score Weighting = 2.0	3	• The overall offloading capacity is 3.75 times larger with an intermediate LCO_2 ship, giving other concepts better cost efficiency. The vessel LCO_2 tanks may not always be full when it offloads, which would impact the scalability of this concept.	5	• The overall offloading capacity is 3.75 times larger with an intermediate LCO_2 ship, meaning that this concept has the highest scalability, as it could take advantage of the higher capacity and therefore serve more customers effectively.	5	• The overall offloading capacity is 3.75 times larger with an intermediate LCO_2 ship, meaning that this concept has the highest scalability, as it could take advantage of the higher capacity and therefore serve more customers effectively.	1	• This concept is limited by the smaller capacity which would effectively put a cap on the revenue that can be generated by this concept due to it being harder to scale up. To reach the scale of the other concepts it would require a very large number of ISO tank containers which would take up too much of the space on the container ship to be considered feasible.

Assessment Criteria	Concept 1		Concept 2		Concept 3		Concept 4	
Costs (CAPEX & OPEX) Score Weighting = 1.0	2	• This concept has a higher CAPEX and OPEX cost per unit of offloading capacity than concepts 2 and 3. • The vessels crew would need specific training with regards to LCO_2 offloading operations which would come at additional cost	3	• This concept has the lowest CAPEX cost per unit of offloading capacity but the highest OPEX cost. • The vessels crew would need specific training with regards to LCO_2 offloading operations which would come at additional cost.	3	• This concept has the highest CAPEX cost of all concepts, however per unit of offloading capacity it is the second best value. • Concept 3 has a slightly lower OPEX than concept 2, with which it is the joint-largest capacity, making this concept the most cost-effective. Whilst the vessel may have to spend a greater amount of time in anchorage, this may be offset by the slightly lower OPEX compared to concept 3. • The vessels crew would need specific training with regards to LCO_2 offloading operations which would come at additional cost.	4	• This concept has by far the lowest CAPEX and OPEX costs, however it also has the smallest offloading capacity. • Concept 4 has the lowest OPEX of all concepts, and the flexibility to generate income from multiple end users at different specifications and purities. • The flexibility of operations decreases the financial risk of this concept. • There will be a dedicated space requirement at container ports for storage of empty ISO tank containers. This area will have to be purchased and maintained which would come at an additional cost.
Ease of Operation Score Weighting = 1.0	4	• There is a chance of incompatibility between vessels and receiving terminals. • This concept only has one offload compared to two in concepts 2/3, reducing the complexity of operations and process control. • Concept 1 relies on jetty availability which may cause delays in offloading. In this scenario the ship may have to wait in anchorage for a jetty to become available which may impact the merchant vessels ability to perform its primary function and meet delivery schedules. • The vessels crew would need specific training in regards to LCO_2 offloading operations.	3	• There is a chance of incompatibility between vessels and receiving vessels / receiving terminals. • Concept 2 is not reliant on availability of jetty availability given that it uses a floating CO_2 storage unit, however this is likely to result in maintenance being more difficult as it is offshore. • This concept has two offloads which increases complexity of operations and control. • The IRV vessel crew would not need any specific training with regards to LCO_2 offloading operations as the crew would be expected to already have IGC training. However, merchant ship crew offloading the LCO_2 will need specific training.	3	• There is a chance of incompatibility between vessels and receiving vessels / receiving terminals. • Concept 3 relies on jetty availability which may cause delays in offloading. In this scenario the ship may have to wait in anchorage for a jetty to become available which may impact the merchant vessels ability to perform its primary function and meet delivery schedules. • This concept has two offloads which increases complexity of operations and control. • The vessels crew would need specific training with regards to LCO_2 offloading operations.	5	• This concept uses existing port infrastructure and container cranes, meaning that there is no chance of incompatibility as ISO is standardised technology. • Concept 4 has the simplest process with minimal process control required, given that the pressure does not need to be maintained in the ISO tank container during offloading, as is the case in the other 3 concepts. • Potential risk around control of container contents and differing vessels with differing OCCS technology. • The vessels crew would not need any specific training with regards to LCO_2 offloading operations. • There will be a dedicated space requirement at container ports for storage of empty ISO tank containers. This area will have to be purchased and maintained which will cost money. • As per the IDMG code, LCO_2 is classified as a non-dangerous good and can be treated as an ordinary container being transferred. This means that there is no impact or concerns with concurrent operations while LCO_2 ISO tank containers are being transferred.

Assessment Criteria	Concept 1		Concept 2		Concept 3		Concept 4	
Safety Score Weighting = 1.0	4	• Given the smaller scale, this concept has reduced manning compared to concepts 2 and 3 and a less complex process control system with less potential points of failure. This results in a smaller amount of number of scenarios that must be considered which would bring about safety risks. • In this concept there may be simultaneous operations taking place which were considered in the SIMOPS review. Loss of containment in these scenarios of either fuel bunkering or LCO_2 offloading may result in affecting other activities in the vicinity. • In scenarios where there are simultaneous operations this may put on a strain on the manpower designation and distribution on the vessel, which must be given extra consideration in safety procedures.	3	• This concept has more potential points of failure due to being more complex. This means that in the HAZID review there is a larger number of scenarios that must be considered which would bring about safety risks. • The LCO_2 being away from the shore where there are other processes avoids cascade failure, however this evens out with the increased risk of having more personnel based offshore • In this concept there may be simultaneous operations taking place which were considered in the SIMOPS review. Loss of containment in these scenarios of either fuel bunkering or LCO_2 offloading may result in affecting other activities in the vicinity. • In scenarios where there are simultaneous operations this may put on a strain on the manpower designation and distribution on the vessel, which must be given extra consideration in safety procedures.	3	• This concept has more potential points of failure due to being more complex. This means that in the HAZID review there is a larger number of scenarios that must be considered which would bring about safety risks. • There is a risk of cascade failure by being located at a liquid bulk terminal, however sufficient procedures will be in place to mitigate this risk to an acceptable level • In this concept there may be simultaneous operations taking place which were considered in the SIMOPS review. Loss of containment in these scenarios of either fuel bunkering or LCO_2 offloading may result in affecting other activities in the vicinity. • In scenarios where there are simultaneous operations this may put on a strain on the manpower designation and distribution on the vessel, which must be given extra consideration in safety procedures.	5	• ISO tank containers are transported in existing hazardous area zones which have safety procedures in place for similar cargo. • This concept requires the least manning of the four concepts, which is beneficial for safety, as this reduces the chance of hazards bringing harm to the personnel. Although the frequent connection and disconnection of the ISO tank containers and the connections subjected to vibrations onboard poses a hazard of leakages. • The expected voyage duration of a containership is expected to be close to the BOG holding time of the ISO tank containers. • As per the IDMG code, LCO_2 is classified as a non-dangerous good and can be treated as an ordinary container being transferred. This means that there is no impact or concerns with concurrent operations while LCO_2 ISO tank containers are being transferred.
Technology Readiness Score Weighting = 1.0	3	• Overall TRL 2, however uses TRL 9 equipment established in other industries which reduces complexity to reach TRL 9	3	• Overall TRL 2, however uses TRL 9 equipment established in other industries which reduces complexity to reach TRL 9	3	• Overall TRL 2, however uses TRL 9 equipment established in other industries which reduces complexity to reach TRL 9	3	• TRL 9, the ISO tank containers for LCO_2 can be purchased from vendors and use existing port infrastructure. The concept of using racks of ISO tank containers and integrating with the ship's machinery for carbon capture is yet to be validated so this would have a TRL of 2.
Operability Score	3rd – 21 points		1st – 27 points		1st – 27 points		2nd – 22 points	

11.6 References

[1] Project Aramis, “CO_2 SPECIFICATIONS FOR ARAMIS TRANSPORT INFRASTRUCTURE,” 2023. [Online]. Available: https://www.aramis-ccs.com/files/ARM-CPT-BB8-PRO-MEM-0033-rev-6.2-public-version-NEW.pdf.

[2] Linde, “201-HG Medical CO_2 G Size,” [Online]. Available: https://shop.linde.hk/shop/en/hk/healthcare-161/medical-co2-161/201-hg-medical-co2-g-size. [Accessed 2023].

[3] BOC, “Carbon Dioxide FOOD FRESH,” 2017. [Online]. Available: https://www.boconline.co.uk/en/images/carbon-dioxide-food-fresh-factsheet_tcm410-450344.pdf.

[4] Imperial College London, “Assessing CO_2 Utilisation UK,” Ecofys, 2017.

12. Policy and Regulations Regime

The availability of the regulatory framework for offloading LCO_2 from ships is essential for the inclusion of the onboard captured CO_2 in the CCUS supply chain, and its seamless transfer to onshore and offshore storage and/or utilisation facilities.

That said, the lack of robust regulatory framework and policies would lead to a delay in the development, implementation and commercialisation of OCCS.

Regulatory and policy frameworks of several countries related to CCS were investigated with the intent of exploring the regulatory readiness as well as advancement in the CCS, and in extension to the endeavour of LCO_2 offloading from ships. The countries were selected based on their potential of early infrastructure development for offloading LCO_2. The review and investigation have been carried out considering the most up-to-date information available at the time of preparing the report in January 2024.

This report provides findings from a high-level review of the policy and regulatory environment in the UK, EU, the USA, Singapore, China, Japan, Korea and Australia pertinent to offloading of onboard captured CO_2 in the form of LCO_2 at major ports. Additionally, the regulatory picture at a domestic level for the Netherlands, Denmark, Iceland and Norway (as part of European Economic Area (EEA)) was also explored to provide additional context. Key issues at an international level are also summarised, with the overall aim to identify regimes that would allow this operation to take place within their national jurisdiction.

For each country/region the following was explored:

- Link to the international policy and regulation picture, in particular the London Convention as amended by London Protocol which governs transfer of CO_2 between two countries.
- The general CCUS policy landscape - which could provide enabling conditions and pathways for new regulation - and any considerations of maritime transport of CO_2 or onboard captured LCO_2.
- The high-level picture of regulation for HSE risk management, pertinent to LCO_2, noting this is often a complex landscape that would require project specific considerations.

This analysis follows a RAG (Red-Amber-Green) system to assess the gaps in accordance with the criteria set out in the table below and shows the extent of the gap in each category in the form of a RAG pie symbol.

RED	AMBER	GREEN
Regulatory framework or policy does not exist for LCO_2 offloading from ships	Regulatory framework or policy does not exist for LCO_2 offloading from ships, but exists either for the onshore CCS value chain or policy is being developed	Regulatory framework or policy exists for LCO_2 offloading from ships, or no adverse regulatory barrier in place

12.1 Introduction to the International Picture

12.1.1 The United Nations

In this section background context and principles relevant to how national and international law views and treats CO_2 is summarised.

CO_2 is the main constituent, by volume, and the common currency (CO_2e) for expressing the concentration of a group of greenhouse gases in the earth's atmosphere responsible for climate change. The United Nations Framework Convention on Climate Change (UNFCCC) is seeking to reduce these greenhouse gases through a series of international commitments and targets. The UNFCCC publishes the national targets and progress towards them monitored through a tightly defined annual process of national atmospheric emissions reporting.

CO_2 is a by-product of many processes that combust fossil fuels to generate energy (for heating, cooling or electricity or motive power generation) and of processes that use fossil fuels as a key input or catalyst to the final product (e.g., fertilisers, chemicals, plastics, infrastructure and construction products). For this reason, CO_2 is often considered and treated as a waste by environmental laws.

Under the UNFCCC's sustainability principles (including "polluter pays" and "proximity" principles) wastes should not be exported but disposed of responsibly, e.g., sequestered permanently, dealt with in a waste handling facility, incinerated in a way that complies with other environmental protection principles and in close proximity to where the waste arises.

Exporting waste is regarded as not complying with these principles. Exporting CO_2 arising from national activities, in particular, would contravene international UN resolutions on national emissions reporting, as it would create a loophole enabling a country to avoid including that CO_2 in its national emissions accounting under the UNFCCC.

The scope of national atmospheric emissions targets under UNFCCC commitments under Annex 1, does not include emissions arising from international transport (aviation and shipping). Note that emissions from these sectors are included in the reporting methodology through monitoring of transport fuel bunkers [1], however these are reported separately from national emissions.

The United Nations Convention on the Law of the Sea (UNCLOS) defines what territory or state has jurisdiction over a vessel during its travel. While transport and storage (T&S) occurs in the territory of a state, the applicable legislation is the law of the sovereign state that applies to all aspects of the T&S facility. In the case of offshore T&S, international law determines which State has the competence to regulate the transport and storage. UNCLOS states that, in the Exclusive Economic Zone (extends 200nm from the coast), all foreign ships enjoy the freedom of navigation, so long as they comply with the general provisions of UNCLOS and international maritime law and that innocent passage may not be denied by the coastal State merely based on the cargo of the ship. Although relevant, UNCLOS presents no regulatory barrier to national or international maritime transport of CO_2.

	The UNFCCC's sustainability principles and decarbonisation targets influence the transport of CO_2 as a waste and as a greenhouse gas. UNCLOS does not appear to present a regulatory barrier to maritime transport of CO_2.

12.1.2 The International Marine Organization

The International Marine Organization (IMO) is an UN agency with specific responsibility for the safety and security of shipping and the prevention of marine and atmospheric pollution by ships. It manages 50 international protocols and conventions (agreements) between 175 member states.

The table below, lists the key IMO conventions and their relationship with CO_2. A summary of the relevant conventions and codes reviewed is provided below.

Table 12.1 – Captured CO_2 end users

Instrument	Instrument full form	Commentary
SOLAS Convention	International Convention for the Safety of Life at Sea, 1974, as amended	This convention covers various aspects of maritime safety including many provisions requiring compliance with Codes of Practice.
IBC Code	International Bulk Chemical Code.	The IBC Code provides an international standard for the safe carriage in bulk by sea of dangerous chemicals and noxious liquid substances listed in chapter 17 of the Code.
IGC Code	The International Code of the Construction and Equipment of Ships Carrying Liquefied gases in bulk.	Code for the construction of ships for carrying bulk liquid with minimum standards for the construction, equipment and operation of ships, compatible with safety.
IMDG Code	International Maritime Dangerous Goods Code.	This code deals with various aspects of maritime safety and chapter VII contains mandatory provisions governing the carriage of dangerous goods in packaged form.
MARPOL Convention	International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto and by the Protocol of 1997.	This convention covers prevention of pollution of the marine environment by ships from operational or accidental causes.
The London Protocol	Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC), 1972 (and the 1996 London Protocol).	Relevant to disposal of captured CO_2 under seabed and it is expected that the cross-country transport of LCO_2 will be governed under this instrument

The IMO through its instruments of IGC Code and IMDG Code make the technical path clear for the transportation of CO_2 as cargo, and there are positive strides towards the transborder transfer being made through amendments of the London Protocol.

12.1.2.1 SOLAS (International Convention for the Safety of Life at Sea)

The main objective of the SOLAS Convention is to specify minimum standards for the construction, equipment and operation of ships, compatible with their safety. Flag States are responsible for ensuring that ships under their flag comply with its requirements, and a number of certificates are prescribed in the Convention as proof that this has been done.

Control provisions also allow Contracting Governments to inspect ships of other Contracting States if there are clear grounds for believing that the ship and its equipment do not substantially comply with the requirements of the Convention - this procedure is known as port State control.

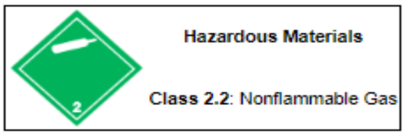
Chapter VII required the carriage of all dangerous goods to be in compliance with the following codes of practice:

- International Bulk Chemical Code (IBC Code)
- International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)
- International Maritime Dangerous Goods Code (IMDG Code)

	We do not consider SOLAS to be directly pertinent to offloading of onboard captured LCO_2 in cargo ports, as their focus is on carriage in international waters.

International Bulk Chemical (IBC) Code
Dangerous goods are classified as follows:

- Class 1 - Explosives.
- Class 2 - Gases: compressed, liquefied or dissolved under pressure.
- Class 3 – Inflammable liquids.
- Class 4.1 - Inflammable solids.
- Class 4.2 - Inflammable solids, or substances, liable to spontaneous combustion.
- Class 4.3 - Inflammable solids, or substances, which in contact with water emit inflammable gases.
- Class 5.1 - Oxidizing substances.
- Class 5.2 - Organic peroxides.
- Class 6.1 - Poisonous (toxic) substances.
- Class 6.2 - Infectious substances.
- Class 7 - Radioactive substances.
- Class 8 - Corrosives.
- Class 9 - Miscellaneous dangerous substances, that is any other substance which experience has shown, or may show, to be of such a dangerous character that the provisions of this Chapter should apply to it.



This symbol / label is derived from the UN-based system of identifying dangerous goods and is used to identify Non-Flammable Gases, i.e., gases which are neither flammable nor poisonous. This includes the cryogenic gases/liquids (temperatures of below -100 °C) used for cryopreservation and rocket fuels, such as nitrogen, neon, and carbon dioxide.

	LCO_2 would qualify as a Hazardous Material under Class 2.2 under IBC code and also under the Globally Harmonized System of Classification and Labelling of Chemicals. This helps to unlock rules for transport of packaged LCO_2.

The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)

The IGC code is a mandatory standard covered by the SOLAS Convention which applies to ships carrying liquefied gases in bulk. It currently covers gases carried by gas carriers at sea and cargoes which include liquefied natural gas and liquefied petroleum gas. This code applies to ships regardless of their sizes and engaged in carriage of liquefied gases having a vapour pressure exceeding 2.8 bar absolute at a temperature of 37.8°C. It sets an international standard for the safe carriage by sea in bulk by stipulating necessary design and construction standards of the ships involved in such carriage to reduce potential risks. It also acknowledges potential hazards that may occur as a result of transforming these gases to a more cryogenic form for carriage using ships.

	Chapter 19 of the IGC code provides a list of gases that require a valid international certificate of fitness for the carriage of liquefied gases in bulk/ an approval for its carriage. Carbon dioxide (high purity and reclaimed quality) is listed under the code as an asphyxiant that requires a valid licence. This can provide a standard for LCO_2 carriers used in offloading solutions. This also informs some domestic categorisation of LCO_2 as a dangerous liquid.

12.1.2.2 International Maritime Dangerous Goods Code (IMDG)

This code deals with various aspects of maritime safety and contains in chapter VII the mandatory provisions governing the carriage of dangerous goods in packaged form. It provides advice on terminology, packaging, labelling, placarding, markings, stowage, segregation, handling, and emergency response.

Packaged goods in ISO tank containers with a designation of UN no. 2187 (Carbon dioxide, refrigerated liquid) fall under this classification.

The Code sets out in detail the requirements applicable to each individual substance, material or article, covering matters such as packing, container traffic and stowage, with particular reference to the segregation of incompatible substances.

	The IMDG Code does not apply to bulk offloading of LCO_2 but does apply to offloading of LCO_2 in ISO tank containers (with some restrictions around volumes), providing a route to international regulation offload of packed onboard-captured CO_2 in the form of LCO_2 (note domestic requirements will also need to be met).

12.1.2.3 International Convention for the Prevention of Pollution from Ships (MARPOL)

The Convention includes regulations aimed at preventing and minimizing pollution from ships - both accidental pollution and that from routine operations - and currently includes six technical Annexes. Special Areas with strict controls on operational discharges are included in most Annexes.

- Annex I - Regulations for the Prevention of Pollution by Oil
- Annex II - Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk. This does not include CO_2.
- Annex III - Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form. This contains general requirements for the issuing of detailed standards on packing, marking, labelling, documentation, stowage, quantity limitations, exceptions and notifications. “Harmful substances” are those identified as marine pollutants in the IMDG Code or which meet the criteria in the Appendix of Annex III.
- Annex IV - Prevention of Pollution by Sewage from Ships
- Annex V - Prevention of Pollution by Garbage from Ships. The definition of ‘Garbage’ in this Annex includes all kinds of food, domestic and operational waste, all plastics, cargo residues, incinerator ashes, cooking oil, fishing gear, and animal carcasses. The operational wastes mentioned do not mention carbon dioxide or other residues from transport fuels. The IMO’s Marine Environment team has setup an online database (PRFD) related to Port reception facilities [2]. This includes for facilities for offloading ship-generated wastes.
- Annex VI - Prevention of Air Pollution from Ships

  IMO guidelines on life cycle GHG intensity of marine fuels (LCA guidelines) account for OCCS in the TtW emissions factor calculation, but the methodological guidance on how the captured CO_2 is accounted for is yet to be developed. IMO’s 2023 GHG strategy includes development of a market-based measure with a technical element and an economic element as a mid-term measure. The IMO’s potential market-based measure will put a carbon price on CO_2 emissions. Though the specifics of the scheme are yet to be worked out, it is expected that it will be in place from 2027 onwards.

  There are no provisions in MARPOL to control the collection of CO_2 onboard, including the ships design for transport and offloading of CO_2 to port, thus leaving it as regulatory grey area.

	MARPOL Annex III potentially applies to the transportation of LCO_2 in packaged form (which includes ISO tank containers). It does not appear to apply to LCO_2 carried in bulk form. It is likely an amendment would be required (e.g. to Annex III or VI) to support offloading of onboard captured CO_2, in the form of bulk LCO_2.

12.1.2.4 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (LC), 1972 and the 1996 London Protocol

The London Convention prevented the export and dumping of toxic and other wastes at sea to reduce marine pollution. It was varied by *The London Protocol*, with Annexes coming into force in 2006 and 2009 making provision for exceptions to this law for certain categories of waste, including CO_2, where it can be proved that the CO_2 is being exported for responsible disposal. This implies a requirement for the CO_2 to be exported only to those countries where national laws already have stringent environmental guidelines for its safe and reliable, permanent storage in geological formations beneath the seabed, and will not be released to the atmosphere.

Many countries have now agreed that shipping CO_2 internationally in order to use 'responsible' CO_2 storage solutions is acceptable and will facilitate establishment and growth of a market for permanent CO_2 storage. This acknowledges the key role that CO_2 storage can plan in reducing the level of CO_2 in the atmosphere currently, at a global level, to help reach decarbonisation targets.

A corollary of permitting the international shipping of CO_2, is that such CO_2 shipping must be tracked from originating country to country and point of final sequestration. This is essential, to provide proof of valid sequestration to authorities in question, including the IMO and the UNFCCC.

The London Protocol 2009 amendment states that *"Two or more countries can therefore agree to export CO_2 for geological storage. To do so they must deposit a formal declaration of provisional application with the Secretary-General of IMO, and also notify IMO of any agreements and arrangements for permitting and responsibilities between the Parties, following the existing guidance."*

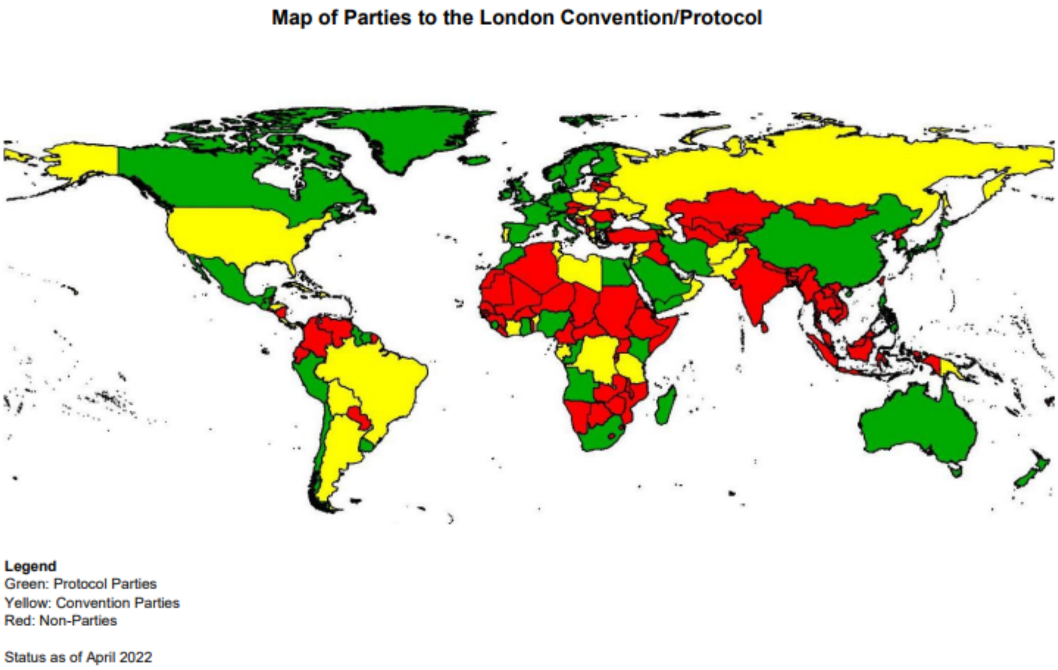


Figure 12.1 – Map of parties to the London convention and protocol

However, for the amendment to be legally binding for all 53 signatory nations, ratification by 2/3 (36) countries is required. This is presently not the case, as shown in Figure 12.1, above. In 2019, the parties to the London Protocol supported a Norwegian–Dutch proposition to allow provisional application of this amendment (via tacit agreement).

The London Protocol sets a regulatory framework for the transport of CO_2 *between countries* and related carbon credits. However, it does not currently cover CO_2 captured in *international waters* being transferred into a country. Potentially in the future the London Protocol can support the offloading of LCO_2 captured in international waters, but it would potentially require an additional amendment.

12.2 United Kingdom

The infographic below from the British Ports Association maps some of the key policy areas relating to ports, showing an opinion on the regulations fit for purpose. Whilst many of the policies and regulations listed will not be relevant to the capture and offloading of LCO_2, it does demonstrate that the policy and regulatory landscape in relation to ports in the United Kingdom is complex and often in need of improvement or major change to reflect societal and industry needs.

A review of some of the pertinent regulations and policies has been carried out, indicating through a RAG rating whether they are a blocker or facilitator to onboard capture and offloading of CO_2. As can be seen, in many of the cases looked at, the policy and regulation are silent on this particular use case, or the has yet to be developed. This provides an opportunity, in that there are no explicit blockers, but also means that further development is likely to have to take place from a regulatory and policy standpoint.

The following sections discuss the high-level regulatory and policy review undertaken for the UK.

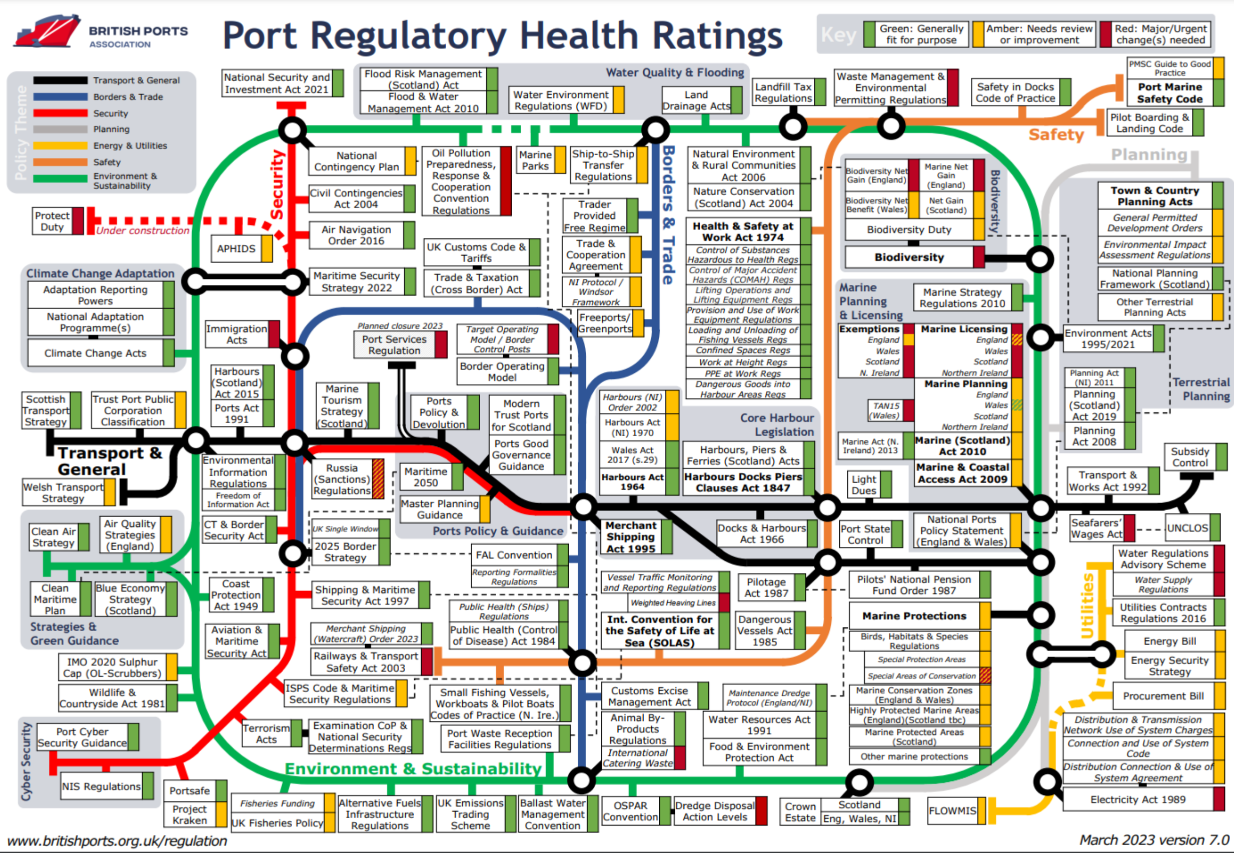


Figure 12.2 – UK Port Regulatory Picture (British Ports Association, March 2023)

12.2.1 Issues Related to International Transport of Captured CO_2

- The Merchant Shipping Regulations, 1986

This act legislates for the IMO's SOLAS convention for the UK and specifically the IMDG codes. It states "No ship to which these regulations apply shall load in bulk or carry in bulk any of the substances listed in chapter 19 of the IGC code unless:

- There is in force in respect of that ship, a valid international Certificate of Fitness for the Carriage of Liquefied in Bulk covering the substance which the ship is loading or carrying or;
- The secretary of State has given specific approval to its carriage.

Under the Merchant regulation, the IGC code applies to all UK ships wherever they may be and to other such ships while they are within the UK or territorial waters. In the case that a ship registered in a state that isn't a party to the SOLAS convention intends to ship LCO_2 within the UK, then this will not apply.

The IGC code places limitations on shipping LCO_2 in bulk within the UK without explicit consent or a Certificate of Fitness. However, the relevant standards do not apply to ships coming from countries outside the UK, that are not parties to the SOLAS Convention.

- Waste policies

As CO_2 is regarded as a waste under international law, each port is an international border for these imports. It is unclear how CO_2 captured onboard ships in international waters will be treated. It is likely that local HSE policies will apply for the handling of the gas, but it is not clear on how captured (and stored) CO_2 will be reported in national atmospheric emissions submissions to the UN is currently unclear.

	Whilst explicit consent, or a certificate, will be required to transport CO_2, the Merchant Shipping Regulations do not mention the offloading of the LCO_2 from (non-gas carrier) cargo ships. As such, this may provide a route for certification of LCO_2 carriers used in offloading but is unlikely to apply to the cargo vessels on which onboard CO_2 is captured. The policies around waste transportation are silent on the transport and offloading of CO_2 that is captured on ships in international waters. Updates to policies such as MARPOL and London Protocol potentially required.

12.2.2 Health, Safety and Environment

The Health and Safety Executive (HSE) is Britain's national regulator for workplace health and safety. It works to protect workers in all work environments, including ports and ships, and is involved in Health and Safety best practice development as well enforcing existing laws.

- Health and Safety at Work Act 1974

This overarching legislation links to a number of regulations that could impact the design and operation of a LCO_2 offloading facility, including:

  - Control of Major Accidents Hazards (COMAH) Regulations
  - Lifting Operations and Lifting Equipment Regulations
  - Work at Height Regulations
  - PPE at Work Regulations

- Dangerous Goods into Harbour Areas Regulations (see below)

At present, we understand that LCO_2 doesn't meet the specification to be covered by COMAH Regulations, but the HSE has identified a gap in the evidence base that could, in the future, bring LCO_2 offloading under COMAH, but likely for situations where it could be released above its critical pressure. As such this appears to be low risk with regard to placing onerous requirements on offloading of onboard-captured CO_2 in the form of LCO_2 in cargo ports.

There are also array of other safety related regulations (as highlighted in Figure 12.2) that could influence requirements for LCO_2 offloading, but we consider it unlikely that they would be prohibitive.

- Dangerous Goods in Harbour Areas Regulations 2016 (DGHAR)

The Dangerous Goods in Harbour Areas Regulations 2016 (DGHAR) [3] contains provisions for safeguarding ports against major accidents involving good classified as dangerous (both packaged and in bulk) as they transit through ports, harbour and harbour areas.

The act, classifies LCO_2 as a Bulk Liquefied Gas and a dangerous good as follows:

- Packaged LCO_2 is classified as dangerous good, as it is classified as dangerous under the IMDG Code (see Section 12.1.2.2)
- Bulk LCO_2 is classified as a dangerous good, as it is a liquefied gas covered under the International Gas Carrier (IGC) Code (see 12.1.2.1).

Dependent on volumes carried, regulations apply to handling CO_2.

Port Authorities enforce the DGHAR, including the following requirements:

- Anyone bringing dangerous goods into a harbour must pre-notify the arrival of the goods to the harbour master and/or berth operator,
- The harbour master is given powers to regulate the movement of dangerous goods within the harbour area when they create risks to health and safety,
- The master of a vessel carrying defined quantities of specified dangerous goods must display appropriate flags and lights,
- Harbour authorities must produce emergency plans to deal with potential consequences of an emergency involving dangerous goods in the harbour area, and any 'untoward incidents' (incidents involving or threatening the containment of dangerous goods) must be reported to the harbour master,
- Berth operators must provide certain information on emergency arrangements to masters of vessels,
- Statutory harbour authorities are given powers to make byelaws on dangerous goods in their harbour area, so a port authority could, for instance, could limit the volume of CO_2 unloaded per vessel, per day or across all vessels visiting the port, per month, etc.

- Environmental regulation and permitting

Offloading of LCO_2 can present risks to nature, for example if a spillage resulted in CO_2 transfer to water this could displace oxygen and impact aquatic life. As illustrated in Figure 12.2, there is an array of environmental and sustainability linked legislation that could influence design and operation of LCO_2 offloading projects.

	The Health and Safety at Work Act and associated regulations are extensive and would need to be explored in detail for implementation of a particular LCO_2 offloading pilot. Overall, we do not see this as prohibiting LCO_2 offloading, rather helping to ensure that it happens in a safe way, but note port-related powers below related to the DGHAR. The DGHAR and associated port rules could potentially provide a framework for safe offloading of onboard captured CO_2 in the form of LCO_2, but it could potentially create some barriers to implementation, depending on individual ports' rules. Project specific review of environmental regulation and permitting would be required to explore the feasibility of an LCO_2 offloading initiative. We consider it most likely that this will influence the location, design and operation of LCO_2 offloading facilities, rather than prohibit this activity at a national scale. Project specific review of environmental regulation and permitting would be required to explore the feasibility of an LCO_2 offloading initiative. We consider it most likely that this will influence the location, design and operation of LCO_2 offloading facilities, rather than prohibit this activity at a national scale.

12.2.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading in Ports

- Carbon Capture and Storage Policy in the UK

The CCUS landscape in the UK has progressed and will be further enabled by the forthcoming Energy Security Bill due to pass into law in early 2024. The permanent sequestration of CO_2 has been established as a key market / export opportunity by UK government due to the rich supply of oil and gas assets on the UK continental shelf which can be reused for this purpose, and the UK's strong portfolio of ports and well-established port facilities, already enabled for handling bulk liquids due to the UK's usage of LNG.

Supportive policies for CCUS are included in the Net Zero Strategy (committing to the UK capturing and storing 20-30 mega tonnes of CO_2e by 2030.) and powers being granted to Parliament via Primary legislation in the renewed Energy Security Bill (Energy Act 2024).

In total, the UK government has committed over £20bn to CCUS, according to the most recent spring budget 2023. This funding will be for a total of four industrial CCUS clusters (two existing and two new). There has also been a £1bn CAPEX funding commitment under the CCS Infrastructure Fund (CIF) for FOAK projects to establish a CCUS industry in the UK.

The marine assets (depleted oil & gas fields, other storage solutions and pipelines to storage areas, etc.) and onshore assets related to storage (gas conditioning plant, gas conditioning and temporary storage, gas injection facilities) will be operated by a "Transport and Storage Company" (T&SCo). These assets will be regarded as regulated asset base and organisations operating CO_2 capture plant will pay regulated pricing for access to the CO_2 transport and storage system. Ofgem, the UK regulator for energy, has been appointed as the CO_2 Regulator and T&SCo operators will be granted a CO_2 T&SCo licence.

Funding through CIF has been granted to two Industrial Clusters with a T&SCo storage site and capture pipeline in each: The Hamilton site off the North-West coast with a coast to storage pipeline from Point of Ayre and the Endurance site off the East coast with a coast to storage pipeline from Teesside. Further CO_2 pipelines from the Humber industrial cluster to either Endurance or Viking fields are anticipated.

Key anchor projects across power generation, hydrogen production and heavy industry will capture CO_2 for sequestration in these CO_2 storage sites will also receive support under a number of Government-approved revenue business models which will contribute to the cost of implementing carbon capture technologies (through CIF) and charges for capacity in the T&SCo facilities. Future CIF funding rounds are currently down-selecting a further two industrial clusters with one or more primary CO_2 storage sites and key anchor projects related to each.

The early funded projects in all selected industrial clusters will start transporting and storing CO_2 emissions from their immediate vicinity, with a rich source of further industrial clients wanting to use the T&SCo facilities once the local store is up and running. Some key emissions sites, however, such as the South Wales Industrial Cluster, are widely dispersed, with no nearby CO_2 storage facility. Transportation to the T&SCo facilities are therefore planned to include shipping CO_2 and opening up the market to facilitate competition and choice for emitters choosing a route to storage for their CO_2 emissions. This adds to the Government ambition to open up UK CO_2 storage sites to receive international CO_2 emissions.

The policy which would allow acceptance of CO_2 from ships, and the business models to subsidise this, are still in development. The government's announcement in March 2023, set out the ambition for the next phase of CCUS in the UK, and stated that the next two T&S networks that apply for funding must *'be able to credibly demonstrate that it can connect via pipeline to at least two projects for an initial phase of capture and non-pipeline transport in future phases'.*

This demonstrates the UK's commitment to utilise non-pipeline transport, which is likely to include CO_2 transfer points within ports. Initially this is expected to for domestic storage (for example transfer from other industrial clusters within the UK). The government do have future ambitions, however, to create a merchant market for CO_2 in the UK.

Some ports within the UK, however, are starting the development to accept CO_2 shipments, on a merchant basis, not requiring government subsidies. The Immingham Port in the Humber Industrial Cluster has been granted Freeport status and has advanced plans for LCO_2 reception facilities with the express intention of facilitating international trade in permanent CO_2 sequestration via pipeline either to the Endurance or Viking storage facilities. Other ports in major industrial sites with nearby CO_2 storage facilities under development are likely to follow suit.

Note that if LCO_2 is offloaded in a UK port for the purpose of reuse or permanent sequestration, CO_2 conditioning will need to take place in the port before it is transported and / or injected into permanent storage, which could be within or outside Port boundaries, but is outside the scope of this study.

- UK Emissions Trading Schemes (ETS) and Carbon Markets

The UK ETS came into effect on January 1, 2021, to address greenhouse gas emissions, in place of the EU ETS following Brexit. It is a cap-and-trade scheme which seeks to reduce greenhouse gas emissions in energy intensive sectors. This limits the total amount of carbon that can be emitted, and participants receive free allowances (carbon allowances) to help with the transition. Depending on their emissions reduction performance, participants are also able to buy or sell emission allowance certificates, trading with other participants in a regulated carbon market, as required.

This creates a market price for CO_2 emissions, and a mechanism to put financial pressure on businesses to reduce CO_2. Carbon emissions reductions are traded as certificates for businesses to buy as part of proving they have reduced their carbon emission. These have to be verified via a certified process in order to be traded in a regulated market. All of this data is part of each nation's submissions to the UN under the internationally agreed carbon reduction targets (as mentioned above).

In July 2023, the ETS Authority published their response to a public consultation “Developing the UK Emissions Trading Scheme” announcing a number of reforms to the scheme. From 2024, the scheme's cap on emissions from the power, industrial and aviation sectors covered by the scheme will be aligned with UK Net Zero targets, accelerating and deepening decarbonisation targets for those sectors. From 2026, the scheme will be extended to cover the domestic maritime transport and from 2028, the waste management sector will also be included.

There are currently no policy statements regarding CO_2 emissions arising that are captured aboard ships in international waters and how these would be treated within the UK ETS. It appears that the ETS Authority have not come to a position on this at this moment in time, especially given the fact that the technology is in its infancy.

- The Energy Act 2008

This UK legislation makes provisions relating to gas importation and storage. Part 1 covers the regulation of gas importation and storage through a licensing and enforcement regime for combustible gas (particularly natural gas and CH_4) and storage of carbon dioxide. It prohibits the exploration or storage of CO_2 without a license, with these licences being granted by the North Sea Transition Authority (NSTA). Provisions that relate to CCS came into effect in 2009.

A license will be required for carrying out the following activities within the territorial sea:

- The storage of CO_2 with a view to its permanent disposal
- Temporary storage of CO_2 (if an interim measure prior to its permanent disposal)
- Conversion of a natural feature for CO_2 storage
- Exploration for a CO_2 storage site
- Establishment or maintenance of an installation for any of these purposes.

The Energy Act does not provide further information on CO_2 transport from storage site using pipelines or ships. However, this offers insights to licensing for CO_2 storage and may in the future include provisions for CO_2 transport from storage sites.

	Supportive of ‘non-pipeline transport’ of CO_2, however, there are not currently business models in place to provide subsidies for transport that isn’t via pipelines. Potential for regime to support offloading of onboard captured CO_2 in the form of LCO_2 in the future. There are currently no working methodologies within the UK ETS for captured onboard ships, or how it would be reported to the UN. Positive moves have been made to include CO_2 from domestic maritime transport which would indicate support for the inclusion of shipping emissions. Further work will be required by the ETS Authority to include captured CO_2. The Energy Act contains requirements for the transport and storage of CO_2, however, these are predominantly based on wider CCUS policy in the UK, and are to enable the establishment of T&SCOs to take CO_2 from emitters to offshore stores. The legislation would not apply to ships that store onboard captured CO_2 but will facilitate the development of T&S networks and offload points for the CO_2.

12.3 European Union (EU)

The offloading of CO_2 at ports is a relatively novel topic. From this research, it has become evident that the policy and regulatory landscape in the EU is quite limited. The current frameworks are mostly focused on the design and operational requirements of the ships and tanks transporting and storing CO_2 in bulk.

Among the reviewed documents is the recent report by ENTEC [4] called *EU regulation for the development of the market for CO_2 transport and storage.* Due to the limited availability of existing CO_2 transport networks and storage sites in the EU, it is important to understand when, where and how these CO_2 networks will grow in the coming decade to link emitters to storage sites.

This section provides an in-depth study, including regulatory analysis of the current regimes, challenges and opportunities, lessons learned from EU regulations, network industries, and CO_2 networks, as well as market analysis on a few selected countries in the EU.

In the regulatory analysis, the focus is on evaluating the regulatory options and (and their limits) for CO_2 transport, regulatory options for CO_2 storage sites (beyond the current CCS Directive), potential business models for the construction and operation of the CO_2 transport networks and analysing the potential business models for the development and operation of the storage sites.

The following regulatory or policy instruments have also been analysed in the ENTEC report:

- OSPAR convention
- The London Protocol (The London Protocol has been discussed in detail in section 3.2.4)
- Environmental liability directive (ELD)
- Emissions inventories, emissions trading etc.
- EU CCS Directive
- EU ETS Directive

Below is an overview of the frameworks from the ENTEC report that have been considered further in our review below. The table below provides an overview of relevant ENTEC referenced documentations highlighted in EU policy section below.

Table 12.2 – Framework from ENTEC report [4]

Regulatory frameworks or policies	Geographical scope	Content scope
EU ETS Directive (European Emissions Trading System)	EU countries plus Iceland, Liechtenstein and Norway (EEA-EFTA states)	Setting standards for emissions from installations in the energy sector, manufacturing industry, aircraft operators and maritime
EU CCS Directive (Directive 2009/31/EC)	EU	Geological storage of CO_2

Regulatory frameworks or policies	Geographical scope	Content scope
EU regulation for the development of the market for CO_2 transport and storage	EU	Regulatory analysis, market analysis, regulatory considerations and policy recommendations

12.3.1 Issues Related to International Transport of Captured CO_2

- Waste policies

As CO_2 is regarded as a waste under international law each port is an international border for these imports. It is unclear how CO_2 captured onboard ships in international waters will be treated. It is likely that local H&S policies will apply for the handling of the gas, but it is not clear on how captured (and stored) CO_2 will be reported in national atmospheric emissions submissions to the UN is currently unclear.

- Carbon Border Adjustment Mechanism (CBAM)

The CBAM is a policy tool that will be implemented by the EU to address the issue of carbon leakage in international trade. The CBAM will enter into application with a transitional phase on 1 October 2023, with the first reporting period for importers ending 31 January 2024. The permanent system will enter into force from 1st of January 2026.

CBAM is designed to cover goods that have a significant carbon footprint and are subject to international trade. It aims to reduce the risk of industries relocating to regions with less strict climate regulations, thereby avoiding greenhouse gas emissions reductions. CBAM imposes carbon tariffs on imported goods based on their embedded carbon content. In the transitional phase the focus is on carbon-intensive products, such as steel, cement, aluminium, fertilizers, hydrogen and electricity. Other goods that will be on the CBAM list from 2026 onwards are still under discussion.

As the CBAM is focussed on carbon intensive goods that are subject to international trade there is no mentioning of carbon capture schemes on vessels in international waters. Indirect emissions, emissions that occur outside the direct production process such as transportation, raw material extraction, etc, are still under discussion by the policy makers.

The CBAM emerged from the EU-ETS scheme. The EU-ETS is an internal EU cap-and-trade system designed to reduce greenhouse gas emissions in the European Union. While CBAM is an additional tool to protect domestic industries and avoid carbon leakage and is an external carbon price. The EU-ETS scheme and the CBAM are two complementary policy mechanism.

	The policies around waste transportation are silent on the transport and offloading of CO_2 that is captured on ships in international waters. Updates to policies such as MARPOL and London Protocol potentially required. At present, we don't see the CBAM applying to or affecting offloading of onboard captured CO_2 in the form of LCO_2.

12.3.2 Health, Safety and Environment

There are several EU directives covering safety aspects of storage, handling and transport of dangerous goods. The EU SEVESO-III directive for control of major chemical accident hazards does not consider LCO_2 a dangerous substance. There are no lower and upper tier thresholds defined. The EU ADR directive for international transport of dangerous goods across EU borders classifies liquid CO_2 as class 2 (pressurised gases) for packaged transport.

The SEVESO III directive is implemented through localised legislation across the EU member states. The ADR is used extensively across the EU and is often the basis to determine the need for safety and environmental risk assessments. The actual assessments appear to be dictated by local regulations.

In the Netherlands for example, the Public Safety Decree (BEVI) does not classify CO_2 as a hazardous substance. A quantitative risk assessment is therefore not required from a public safety perspective. From an environmental and working conditions perspective however, CCS facilities do require a risk assessment according to the Dutch Environmental Management Act (Wm) and the Working Conditions Decree (Arbowet). These refer indirectly to the guideline PGS-9 for storage of LCO_2.

The primary risks associated with the process of offloading LCO_2 at ports in all EU countries would be determined by:

- Volumes of liquefied CO_2 offloaded;
- Potential loss of containment scenarios;
- Storage in the vicinity of fire hazards (which may lead to BLEVE);

	The EU and national HSE regulation landscape is extensive and would need to be explored in detail for implementation of a particular LCO_2 offloading pilot. There is a mixed picture across the EU for how LCO_2 is classified and therefore the requirements put in place in relation to HSE. There is potential for this to limit the feasibility of certain applications for offloading, but also may allow offloading with the appropriate design and operational risk mitigation measures in place.

12.3.3 Policy landscape for CCUS pertinent to CO_2 offloading in ports

Below an overview with some key outtakes of the international, maritime, EU and selected country specific policies which are pertinent to CO_2 offloading in ports. Not all EU countries have been assessed.

12.3.3.1 European Union (EU)

- European Emissions Trading System (EU ETS)
  - Operators conducting activities that are incorporated in the EU ETS must annually surrender allowances corresponding to the total amount of emissions that are subject to the trading system.
  - The EU ETS can be said to support CCS in that CO_2 from activities subject to the EU ETS that has been captured and stored can be subtracted from the operators' emissions accounting, meaning that the operator does not need to surrender allowances for this volume.

- The EU ETS regulations explicitly regulate transport by pipelines, but make no mention of transport by ship, which can result in some legal issues which has been seen in Norway where CO_2 from a heat plant was transported via ship, not pipeline.
- In July 2020, the European Commission approved Norway's interpretation of the regulations, allowing capture facilities to deduct the CO_2 from their emissions accounting when the CO_2 is transferred from the ship to the reception terminal.
- From January 2024, EU ETS will apply to maritime transport. The EU ETS puts a carbon price on CO_2 emissions and shipping companies will need to surrender sufficient EU Allowances, to cover 40% of their fleets' 2024 TtW CO_2 emissions. By 2027 they will need to surrender allowances for all emissions. The EU ETS Directive provides specific provisions with regards to CCUS technologies. It is not needed to surrender allowances for the following:
  - CO_2 captured and transferred to an installation to be stored in a storage site in accordance with the CCS Directive;
  - CO_2 utilised to become permanently chemically bound in a product so that it doesn't enter the atmosphere (subject to the conditions to be set out in the implementing acts under development; adoption is expected in the course of 2024).

- The Storage Directive or CCS Directive (Directive 2009/31/EC)
  - The Storage Directive (Directive 2009/31/EC) established by the European Parliament and the Council on 23 April 2009, outlines the legal framework for the secure and environmentally sound storage of carbon dioxide (CO_2).
  - At the international level, legal barriers to the geological storage of LCO_2 in geological formations under the seabed have been removed through the adoption of related risk management frameworks under the 1996 London Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (1996 London Protocol) and under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention).
  - Provides four nonbinding guidance documents:
    - GD1 – CO_2 Storage Life Cycle Risk Management Framework;
    - GD2 – Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures;
    - GD3 – Criteria for Transfer of Responsibility to the Competent Authority;
    - GD4 – Financial Security and Financial Mechanism.

- SEVESO III Directive

  The EU SEVESO-III directive for control of major chemical accident hazards does not provide lower and upper tier thresholds for liquefied carbon dioxide. This directive would not be applicable to offloading CO_2 in ports.

- Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

The registration, Evaluation and Authorization of Chemicals (REACH) is a legislation applying to all EU member states for the handling of chemical substances. It entered into force on June 2007, and is meant to promote the protection of human health and the environment.

- EU ADR Directive

  The EU ADR Directive covers classification of packaged dangerous goods across all EU nations. As stated above, the baseline classification is almost identical to that used by IMDG.

	There is some precedent for recognising maritime transport of CO_2 in the EU ETS, but transport of onboard captured CO_2 in the form of LCO_2 may require additional policy development. We did not identify any explicitly prohibitive regulations at an EU level, but it is apparent that offloading of onboard captured CO_2 in the form of LCO_2 is outside of the consideration of some existing frameworks, so further development of regulation may be required to enable offloading.

12.3.3.2 Denmark

The general attitude towards CCS in Denmark is very positive, and CCS strategies/roadmaps are in place, securing that CCS can happen from 2025.

A number of potential geological structures have been investigated in terms of their CO_2 storing potential. The Former oil and gas field Nini has been designated as the first CO_2 storage location under the Greensand project, and an agreement has been concluded with Belgium on the permanent storage of CO_2.

CCS is such a novel area in Denmark, that no specific legislation regarding CO_2 *captured in international waters* are in place yet. This means that the offloading falls under other already existing regulations.

- The Danish Climate Act (2019)

  Main objective of the Danish Climate Act is to reduce GHG emissions with 70 % by 2030 and reach climate neutrality by 2050.

- Climate Agreement for Energy and Industry (2020)

  CCS constitutes an essential element in achieving the climate policy objectives enshrined in Climate Act.

- A Roadmap for CO_2 Storage – First Part of a Comprehensive CCS Strategy (2021)

  The agreement starts the process for granting permits for CO_2 storage in the Danish underground in the North Sea, so that storage in spent oil and gas fields will be possible as early as 2025. At the same time, the agreement enables the import, export and transport of CO_2 across national borders.

  The parties to the agreement agree that Denmark must be able to import and export CO_2 to and from abroad. The parties to the agreement note that this requires the removal of a number of regulatory barriers. The parties to the agreement therefore agree to accede to the amendment to the London Protocol and the amendment to the Marine Environment Act (proposed November 2021) to enable the import and export of CO_2 with selected countries [5].

- A Roadmap for the Capture, Transport and Storage of CO_2- the Second Part of an Overall CCS Strategy (2021)

  In December 2021, the Danish government and a broad political majority followed up on the agreement on the first part of an overall CCS strategy with this agreement [6].

  The agreement on the entire value chain, i.e., capture, transport, storage and use of CO_2, intends to ensure that the first facilities for CO_2 capture and storage are in operation in Denmark in 2025.

- Framework conditions for CO_2 storage in Denmark (2022)

  On 21 June 2022, the government and a broad political majority entered into an agreement on framework conditions for CO_2 storage in Denmark as a follow-up on Denmark's CCS strategy [7].

  With the agreement, it has been decided that the state will become a co-owner of permits for CO_2 storage in Denmark. The parties to the agreement agree that the state ownership must be handled by the Nordsøfonden, which is assessed to have the necessary experience and competences to safeguard the state's interests from participation in the oil and gas activities.

- The Merchant Shipping Act

  The main legislative framework for Danish maritime law is the Merchant Shipping Act (MSA) which to a large extend is based on international maritime conventions.

  The MSA is complemented by the Administration of Justice Act (AJA), which covers general procedural matters, and other specific laws pertaining to various areas of legislation. Furthermore, the significance of EU law has been growing, particularly concerning safety, offshore operations, and environmental concerns [8].

  Chapter 13 of the MSA regulates contracts of carriage, following the guidelines outlined in the Hague-Visby Rules. The SDR Protocol of 1979, which Denmark has ratified, is also incorporated into these regulations. While Denmark has not ratified the Hamburg Rules in their entirety, certain provisions of these rules have been included within the MSA. Additionally, Denmark has signed but has yet to ratify the UN Convention on Contracts for the International Carriage of Goods Wholly or Partly by Sea 2009, also known as the Rotterdam Rules.

- The Safety at Sea Act

  The Safety at Sea Act (SSA) establishes the primary responsibilities concerning navigation and safety at sea in Denmark.

  It is based on international conventions such as the International Convention for the Safety of Life at Sea 1974 (SOLAS), the International Convention on Load Lines 1966 (the Load Lines Convention), the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers 1995 (the STCW Convention) and the International Convention for the Prevention of Pollution from Ships 1973 (as modified by the Protocol of 1978) (MARPOL (73/78)) and various EU regulations.

- Technical Regulations for Gases

  The Technical Regulations for Gases by the Danish Emergency Management Agency regulates the transport and storage of gases.

- Port control

Denmark has ratified SOLAS (International Convention for the Safety of Life at Sea) and the Paris Memorandum of Understanding on Port State Control 1982 (Paris MOU). The Paris MOU necessitates contracting states to carry out effective port state control inspections on vessels from any jurisdiction.

	There are positive policy and regulatory developments in Demark relating to CCUS. These could provide a foundation for development of supportive policy for offloading of onboard captured CO_2 in the form of LCO_2, but specific policy or guidance may need to be developed for this application.

12.3.3.3 Iceland

Iceland is part of a joint commitment with the EU Member States to reduce greenhouse gas emissions by 55% by 2030 [9].
Iceland is generally considered one of the leading countries in the World when it comes to CCS.
The CCS Directive entered into force in 2015 and was amended in 2021, allowing for industrial scale storage.
Regulation based on the CCS Directive is under construction.

- Act No. 119/2012 on the Icelandic Transport Authority (ICETRA)

  This act lays out the responsibilities and jurisdiction of The Icelandic Transport Authority and describes how the Authority conducts administration and regulation pertaining to aviation affairs, harbour affairs and matters concerning sea defences, maritime affairs, traffic affairs, and road affairs.

  Article 5 describes that the Authority is responsible for the oversights of transport structures.

  Article 9 describes the Authority's tasks related to maritime affairs.

- Act on Maritime Security

  The Icelandic Act on Maritime Security ensures "that ship, crew, passenger, cargo and port facility security is not compromised by terrorist threats of any kind and other unlawful acts."

  This includes security measures in accordance with SOLAS and the ISPS Code (International Code for the Security of Ships and of Port Facilities) [10].

  Chapter 2 relates to ship security, while port facility security is treated in Chapter 3, and cargo security in Chapter 4.

	There are positive policy and regulatory developments in Iceland relating to CCUS. These could provide a foundation for development of supportive policy for offloading of onboard captured CO_2 in the form of LCO_2, but specific policy or guidance may need to be developed for this application.

12.3.3.4 Norway

"For many years, various Norwegian governments have supported technology development, test and pilot projects, and underscored the importance of carbon capture and storage as an important climate tool internationally. The present Government has followed up this work and made targeted efforts on CCS since 2013." – The Norwegian Government, Longship press release 2020 [11].

There are several (international and) national laws and regulations that comprise the framework for CCS in Norway.

- The London Protocol

  Norway has ratified the London Protocol, and was one of the leading forces behind the 2009 amendment to article 9 (which Norway approved in 2010), as this was needed for the Norwegian government to be able to proceed with their formal proposal in September 2020 for their Longship CSS project and Northern Lights transport and storage facility, which plans to receive CO_2 from across Northern Europe [12].

  The fact that the 2009 amendment has not formally entered into force is a legal obstacle to cross-border cooperation on CCS (though it is possible to avoid the obstacle by provisionally accepting a resolution published in 2019, which allows for contracting parties to provisionally accept the adopted (but not yet accepted) amendments to the London Protocol to allow transboundary movement of CO_2 as waste but it is unclear if this has any effect on transfer of CO_2 captured in international waters.

- Norwegian maritime law: Joint responsibility

  In Norway, multiple ministries are responsible for different laws with influence on the maritime sector.

  - Ministry of Trade and Industry
    - The Ship Safety and Security Act 2007
    - The Norwegian Maritime Code 1994, Ch. 1 I-II Ch 2 Ch 5 Ch 10 II, Ch. 2, Ch. 5, Ch. 10, Ch. 18
    - The Seaman's Act 1975
  - Ministry of Justice and the Police
    - The Norwegian Maritime Code 1994
  - Ministry of Fisheries and Coastal Affairs
    - The Harbour and Fairways Act 2009
  - Ministry of the Environment
    - The Pollution Control Act 1981

- The Maritime Code 1994

  The Maritime Code is administrated by Ministry of Justice. Certain parts are delegated to the Ministry of Trade and Industry by Regulation 20th December 1996 No. 1156. It covers substantial aspects of shipping-related business.

- Harbour Act 1984

  The purpose of this Act is to facilitate the best possible planning, development and operation of harbours, and to safeguard traffic. The Act gives the ministry the right to lay down regulations or make individual decisions concerning a number of things, amongst others *"the unloading, loading, storage and transport of hazardous substances and goods within the harbour district"* (§11, 3).

- The Harbour and Fairways Act 2009

  The purpose of this Act is to facilitate and operate harbours and to safeguard waterway traffic. The Ministry of Fisheries and Coastal Affairs' duties are to be carried out by National Coastal Administration.

- Ship Safety and Security Act 2007

  The purpose of the Ship Safety and Security Act is to safeguard life, health, environment and tangible assets. Regulatory framework. Details are in the Regulations. Regulatory Agency that contributes to the promotion higher ship safety level. Scope of application: Norwegian and foreign flagged (only within Norwegian jurisdiction) vessels over 24 meters in length or used in trade.

  Regulatory framework contains safety management requirements for all ships (ch. 2), ship and crew certificate requirements (ch. 3), crew safety (ch. 4), environmental safety (ch. 5), security and terrorism (ch. 6), supervisory body (ch. 7), administrative measures (ch. 8), administrative sanctions (ch. 9), criminal liability (ch. 10).

- Pollution Control Act

  The purpose of this Act is to protect the outdoor environment against pollution and to reduce existing pollution, to reduce the quantity of waste and to promote better waste management.

- Act relating to safe containers

  This Act (last amendment in 2015) applies to containers used in transport to or from Norway or in transit through Norway, except for containers for air transport.

- Dangerous Goods Regulations

  - The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code)

  - Safety of Life at Sea Convention (SOLAS) Chapter VII.

- Carriage of hazardous and noxious liquid substance in bulk on existing offshore support vessels after 31 December 2020

  These requirements applicable for all ships, including existing offshore support vessels (OSVs) engaged in the transportation of chemicals in bulk. Ship owners are advised to consider the most suitable approach to ensure their OSVs remain fit for their intended purpose. This circular provides comprehensive information on the approach taken by the Norwegian Maritime Authority (NMA) to address the impact on existing OSVs, while also highlighting potential challenges that may arise.

  "The Environmental Safety Regulations and the Dangerous Goods Regulations apply when carrying NLS, including chemicals, in bulk. These regulations require ships to comply with MARPOL Annex II or SOLAS Chapter VII Part B, both of which make the IBC Code mandatory. As an alternative to the IBC Code, an OSV carrying limited amounts of hazardous and noxious liquid substances may comply with the appropriate IMO guideline."

- Norwegian research initiatives supporting CCS

CLIMIT is a national program in Norway that focuses on research, development, and demonstration of technologies for carbon capture, transport, and storage. The program aims to provide support for the advancement of knowledge, expertise, technology, and solutions in order to drive cost reduction and facilitate widespread global adoption.

Technology Centre Mongstad (TCM) is a testing facility for the development, testing and qualification of carbon capture technology, owned by industry partners and the Norwegian State.

The Norwegian Government and the current industry owners of TCM have entered into a new operating agreement for the period from the end of August 2020 until the end of 2023. In this agreement, the government aims to enhance industry participation and secure additional industry funding for TCM.

The Norwegian CSS Research Centre (NCCS) is a research center dedicated to carbon capture and storage. It started up in 2016 and will have a duration of eight years.

There are positive policy and regulatory developments in Norway relating to CCUS. These could provide a foundation for development of supportive policy for offloading of onboard captured CO_2 in the form of LCO_2, but specific policy or guidance may need to be developed for this application.

12.3.3.5 Netherlands

The Netherlands is part of a joint commitment with the EU Member States to reduce greenhouse gas emissions by 55% by 2030.

CCS is also a novel area in The Netherlands with no specific legislation regarding CO_2 captured in international waters in place yet. This means that the offloading would fall under other already existing regulations.

One of the prevalent discussion points is how to classify CO_2 captured in international waters: is it a commodity or a waste stream?

As stated above, CCS (as an activity) requires an environmental risk assessment according to the Dutch Environmental Management Act (Wet Milieubeheer) and a safety assessment in accordance with the Working Conditions Act (Arbowet). There is also mention of CCS in several other regulations such as the Dutch Mining Act (Mijnbouwwet), Nature Conservation Act (Wet Natuurbeheer), the Water Act (Waterwet) and the Soil Protection Act (Wet Bodembescherming).

Specific demands on the bulk storage of liquefied CO_2 are covered in the guideline (BAT-) document PGS-9. This document is referred to via the Dutch Environmental Management Act.

The Public Safety Decree (Besluit Externe Veiligheid Inrichtingen) does not classify CO_2 as a hazardous substance. A quantitative risk assessment from this perspective would therefore not be required.

On January 1 2024, a substantial change in legislation in the Netherlands will take effect called the Omgevingswet. Current legislation will be restructured, simplified and renamed. CCS will likely be classified as an (potentially) environmentally harmful activity requiring a risk assessment and an environmental permit. This is meant for carbon capture and storage in geological structures, not for offloading at ports of carbon captured in international waters.

	There are positive policy and regulatory developments in Netherlands relating to CCUS. These could provide a foundation for development of supportive policy for offloading of onboard captured CO_2 in the form of LCO_2, but specific policy or guidance may need to be developed for this application.

12.4 United States of America

12.4.1 Issues Related to International Transport of Captured CO_2

The United States works with countries around the world to reduce and prevent pollution caused by among other things, ocean dumping. The London Protocol, which aims to prevent dumping at sea and the exporting of waste, was signed by the United States on March 31, 1998, and entered into force on March 24, 2006 however the treaty is yet to be ratified.

As CO_2 is regarded as a waste under international law each port is an international border for these imports. It is unclear how CO_2 captured onboard ships in international waters will be treated. It is likely that local H&S policies will apply for the handling of the gas, but it is not clear on how captured (and stored) CO_2 will be reported in national atmospheric emissions submissions to the UN is currently unclear.

	The policies around waste transportation are silent on the transport and offloading of CO_2 that is captured on ships in international waters. Updates to policies such as MARPOL and the London Protocol are potentially required.

12.4.2 Health, Safety and Environment

CO_2 is considered an asphyxiant gas, when liquefied it is also classified as cryogenic. The U.S. Occupational Safety and Health Administration (OSHA) sets a PEL of 5,000 ppm (0.5% by volume) over eight hours for CO_2. The National Institute for Occupational Safety and Health (NIOSH) has established 40,000 ppm (4% by volume) as the immediately dangerous to life or health (IDLH) for CO_2. For comparison, typical outdoor CO_2 concentration is 300-400 ppm (0.03% - 0.04%) but can be as high as 600-900 ppm in metropolitan areas.

The two entities with national applicability for the safe handling, transporting, and storing of gases are the CGA and NFPA. The following standards are specific to CO_2 and liquid CO_2 requirements:

CGA G-6.1: Standard for Large Insulated Liquid Carbon Dioxide Systems at User Sites

CGA G-6.4: Safe Transfer of Liquid Carbon Dioxide in Insulated Cargo Tanks, Tank Cars, and Portable

CGA G-6.5: Standard for Small Stationary Insulated Carbon Dioxide Supply Systems

CGA G-6.6: Standard for Carbon Dioxide Bulk Transfer Hoses

NFPA 55: Compressed Gases and Cryogenic Fluids Code

The National Environmental Policy Act (NEPA) is the principal federal law that dictates how environmental review and permitting works at the federal level. NEPA imposes procedural requirements on federal agencies. For any particular federal agency, compliance may require assessing the activities of other entities, inside or outside government. Projects in the private sector may be subject to NEPA if they have a federal nexus—for example, if they need a significant federal permit or involve federal land, federal funding or federally managed infrastructure. The NEPA process is conducted by the federal agency or agencies that are connected to the project's particular federal nexus. [13]

A federal permit may be required under the Clean Water Act if a CCS project or pipeline crosses water or wetlands. The Army Corps of Engineers issues permits for discharge of dredge or fill materials under Section 404 of the Clean Water Act. Section 404 requires a permit for any utility line crossing that requires the discharge of dredge or fill materials into US waters. This includes "any pipe or pipeline for the transportation of any gaseous, liquid, liquescent or slurry substance for any purpose" [13].

The federal Environmental Protection Agency's (EPA's) Greenhouse Gas Reporting Program requires reporting of GHG data and other relevant information from large GHG emission sources, fuel and industrial gas suppliers, and carbon oxide injection sites in the US. This includes information regarding the capture, supply and underground injection of carbon oxide in the US. Approximately 8,000 facilities are required to report their emissions annually, and the reported data are made available to the public each year.

When offloading CO_2 at U.S. ports, federal pipeline regulations are potential barriers that would limit where and how LCO_2 transfers can occur at ports. Pipeline regulations include all parts of those facilities through which gas moves in transportation, including pipes, valves, regulator stations, holders, and fabricated assemblies. Although CO_2 is not considered a hazardous material by the U.S. Department of Transportation, CO_2 pipelines are regulated because of the operating pressures of these pipelines. These regulations are outlined under Title 49 of the Code of Federal Regulations (CFR), Part 195, Transportation of Hazardous Liquids by Pipeline, which applies to the transportation of hazardous liquids and carbon dioxide. Under the U.S. Department of Transportation, the Pipeline and Hazardous Materials Administration (PHMSA) is responsible for regulating the movements of all hazardous materials, including pipelines in the United States. PHMSA sets the standards for safe construction and operation of CO_2 pipelines, including technical design specifications and the requirements for mechanical integrity management. States can act as the pipeline regulator if, at a minimum, their regulations comply with federal regulation.

Since 2011, MARPOL Annex I, Chapter 8 regulates ship-to-ship (StS) transfers for oil tankers, specifically those with a capacity of 250+ barrels, or oil tankers of 150 gross tonnage and above. These vessels are also required to have an STS operations plan that is approved by their respective flag country. There is no such requirement under MARPOL Annex II for chemical cargo. However, the ISM provides for all types of vessels to have onboard procedures for key operations such as STS transfers. The *OCIMF Ship-to-ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases* identifies best practice guidelines when conducting STS transfers for liquefied gases such as CO_2.

US HSE regulations are extensive and would need to be explored in detail for implementation of a particular LCO_2 offloading pilot. Overall, it is not seen this as prohibiting LCO_2 offloading, rather helping to ensure that it happens in a safe way, but requirements could affect the feasibility of particular projects.

12.4.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading In Ports

In the United States, the process for permitting a CCUS project is similar to that for any industrial activity, and the CEQ CCUS Report recognized that the Federal Government has an existing regulatory framework that is capable of safeguarding the environment, public health, and public safety as CCUS projects move forward.

In general, government support for CO_2 transport and storage infrastructure is growing. First introduced in 2008, Section 45Q of the Unites States Internal Revenue Code provides a tax credit for CO_2 storage. The policy is intended to incentivize deployment of CCUS, and a variety of project types are eligible. In 2022, the US introduced a significant stimulus for CCUS investment with the passage of legislation (the Inflation Reduction Act) to expand and extend the 45Q tax credit. Although these policies are aimed at industrial facilities and power plants, these financial benefits are likely to apply to onboard carbon capture and storage in the future.

Facilitated by the Infrastructure Investment and Jobs Act, the Department of Energy in the United States announced more than USD 90 million for 11 large-scale CO_2 storage projects awarded under the "CarbonSAFE Phase II" funding opportunity in 2023. In addition, the United States also announced more than USD 2 billion in funding towards projects eligible under CarbonSAFE Phase III and IV for site characterisation, permitting and construction.

The CEQ CCUS Report recognized that to reach the President's ambitious climate goal of net-zero emissions economy-wide by 2050, the United States will likely have to capture, transport, and permanently sequester significant quantities of carbon dioxide. There is growing scientific consensus that, while the first priority for addressing climate change must be to avoid emissions, CCUS technologies and permanent sequestration are likely needed to prevent the worst impacts of climate change. To advance these aims, the President is committed to increasing support for CCUS research, development, demonstration, and deployment (RDD&D), enhancing the Section 45Q tax incentive for CCUS and appropriately implementing the robust and effective regulatory regime that exists in the United States.

There are however many permits that could be required in order to transport, offload and store CO_2 for geological sequestration. The following permits could be required from the Federal Government or, if applicable, the designated state/territorial/Tribal agency for a CCUS project, depending on project specific facts:

- Marine Protection, Research and Sanctuaries Act (MPRSA) permit for transport, including by pipelines, and geological sequestration in marine environments.
- Outer Continental Shelf Lands Act (OCSLA) permit for rights-of-way for offshore pipelines, lease for offshore energy and mineral resources, and/or permit for offshore injection wells. The statue has never been used to authorize permanent CO_2 storage.

When looking specifically at U.S. ports, they are not operated by the federal government but are merely regulated by the federal government. There are over 2,400 port facilities in the U.S. that are owned by either state, local, or private entities. Federal laws and regulations control the operations of these ports, their serving of vessels, and their competitive nature.

There is growing policy support for CCUS in the US, including for transport and storage of CO_2. There is a supportive financial environment for investment in CCUS that may apply to onboard carbon capture and storage in the future.

12.5 Singapore

12.5.1 Issues Related to International Transport of Captured CO_2

Singapore has not ratified the London Convention or the London Protocol. There is no regulatory framework in place in Singapore relating to international transport of carbon dioxide in bulk. Carbon dioxide is being imported and exported as industrial goods in packaged form in ISO tank containers.

	The policies around waste transportation are silent on the transport and offloading of CO_2 that is captured on ships in international waters. Updates to policies such as MARPOL and the London Protocol are potentially required.

12.5.2 Health, Safety and Environment

Based on the International Chemical Safety Cards (ICSCs), LCO_2 is considered not combustible. Under transportation UN Classification it is classified as UN Hazard Class: 2.2. According to UN GHS Criteria refrigerated gas; may cause cryogenic burns or injury. There is no flash point applicable to LCO_2. The gas is heavier than air and may accumulate in lowered spaces causing a deficiency of oxygen. It decomposes above 2000°C which can produce toxic carbon monoxide.

In Singapore, MPA with the approval of the Ministry for Transport and National Environment Agency has made regulations which do not identify UN Hazard class 2.2 as Dangerous Goods. The quantity of First Schedule dangerous goods which may remain onboard any vessel at any Jurong Port container berth, PSA container berth, conventional berth, the Tuas Jetty or the Sudong Explosive Anchorage is set out in Table 1 to 6 outlining key berths and IMO class. Refer Maritime and Port Authority of Singapore (Dangerous Goods, Petroleum and Explosives) (Amendment) Regulations 2021 - Singapore Statutes Online (agc.gov.sg) The list currently does not have any regulations on UN Hazard class 2.2.

We have not identified further specific policy and regulations regimes that may prevent or enable offloading of captured CO_2 from ships in Singapore at present, beyond the international issues identified. From an operational point of view, the quality and property of the captured LCO_2 may need conform to industry standards such that it can be discharged in the terminal per existing practices. Otherwise, deviation may necessitate a separate process to review and manage the discharging process into Singapore.

Chemicals regulated under the Fire Safety (Petroleum & Flammable Materials) Regulations are divided into three groups – petroleum, flammable materials and mixtures that contain petroleum and / or flammable materials. This classification, by Singapore Civil Defence Force (SCDF), is based on the chemical flash points and UN Class as indicated here - General Information of P&FM Licence | SCDF, but both the properties of these are not applicable for LCO_2.

	The HSE picture for bulk transfer of LCO_2 in Singapore is uncertain, but we have not identified any prohibitive regulations.

12.5.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading In Ports

The maritime legislation of Singapore includes Acts of Parliament in Singapore that affect the port of Singapore and ships registered under the Singapore flag. As an important international maritime center, much of the Singapore legislation is transposed from IMO maritime conventions, to be more consistent with international maritime standards.

Costs for carbon capture are relatively high in Singapore. Generally, capture costs are lower for processes that have a high output pressure of flue gas and high concentrations of CO_2. These sources do exist in Singapore and represent fairly small amounts of CO_2. The largest share of emissions comes from gas-fired power plants, which also represents the highest cost. In addition, CO_2 capture units would need to be retrofitted to the existing plants in Singapore. Specifically, for low-concentration CO_2 streams, the absorber capacity needs to be significant and solvent-based capture units would require a substantial amount of land which is a barrier in a country that is already land-constrained.

CO_2 transport by ship is more attractive in scenarios where small CO_2 volumes need to be transported over long distances. The ships for CO_2 transport at large scale (10,000–40,000 m3) have been proposed but are not built yet. Combining CO_2 transport with multi-purpose ships that are used for LNG/ethylene transport seems feasible and may prove to be a cost-efficient way of transporting CO_2.

	The policy picture for CCUS and specifically onboard captured CO_2 is immature but we have not identified any prohibitive regulations.

12.6 Australia

Australia has a relatively robust regulatory framework and policies that are conducive to the implementation and commercialization of CCS onshore and offshore within the jurisdiction of the country. However, with the legal framework regulating CCS developments in Australia being divided among Commonwealth laws and State laws, the Commonwealth CCS laws apply to the offshore areas within its jurisdiction and the State laws apply to the onshore and offshore CCS projects within their jurisdiction.

The states of Victoria, South Australia and Queensland have legislation in place to regulate CCS projects, the other three states do not have CCS specific legislations in place yet.

In the most recent development, a bill has been presented in the parliament with recommendations that the Australia Government ratify both the 2009 and the 2013 amendments to the London Protocol, and if passed, development of bi-lateral agreements with foreign countries and CO_2 project developments can proceed.

12.6.1 Issues Related to International Transport of Captured CO_2

- Environment Protection (Sea Dumping) Act 1981

Australia is a party to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the London Protocol. Australia has implemented the protocol domestically since 2000 under the Environment Protection (Sea Dumping) Act 1981.
The Act places Australia in compliance with its international obligations under the London Protocol, and its 2006 amendment that allows allow Contracting Parties to sequester CO_2 in their jurisdiction.

	There is no regulatory framework in place for international transport of captured CO_2 yet but there are no prohibitive regulations noted in this respect. Additionally, Australia is in process of ratify both the 2009 and the 2013 amendments to the London Protocol.

12.6.2 Health, Safety and Environment

- Hazardous Chemical Information System (HCIS)

Safe Work Australia maintains the Hazardous Chemical Information System (HCIS) database of chemical classifications and workplace exposure standards that aligns mostly with the GHS.
The Exposure Standards towards asphyxiation are available but CO_2 is not included in the Hazardous chemicals list within Hazardous Chemical Information System (HCIS)

- Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act)

The act makes provision for where the offshore CCS injection or storage activity may have impacts on matter of national environmental significance.
The act is relevant to the downstream part of the CCS supply chain involving storage of the LCO_2 in offshore areas and which could prospectively include LCO_2 offloaded from ships.

	There are no prohibitive regulations noted from the HSE perspective that could be a barrier to the offloading of captured LCO_2 from ships. However, there are instances where CO_2 is not included in the Hazardous chemicals list.

12.6.3 Policy landscape for CCUS pertinent to CO_2 offloading in ports

- Offshore Petroleum and Greenhouse Gas Storage Act 2006 (OPGGS Act)

The act provides a regulatory framework for petroleum exploration and recovery, and the injection and storage of greenhouse gas substances in the offshore areas.

It is relevant to the downstream part of the CCS supply chain involving transportation and storage of the LCO_2 in offshore areas and which could prospectively include LCO_2 offloaded from ships.

- Offshore Petroleum and Greenhouse Gas Storage Amendment (Cross-boundary Greenhouse Gas Titles and Other Measures) Bill 2019

The bill amends the Offshore Petroleum and Greenhouse Gas Storage Act 2006 in providing for the grant and administration of single GHG titles that straddle the boundary between Commonwealth waters and state or Northern Territory (NT) coastal waters; enable unification of adjacent Commonwealth GHG titles; and strengthen and clarify the powers of National Offshore Petroleum Safety and Environmental Management Authority inspectors during oil pollution emergencies.

The bill provides the framework for offshore CCS development and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- Greenhouse Gas Geological Sequestration Act 2008

The Act is to facilitate and regulate the injection of greenhouse gas substances into underground geological formations for the purpose of permanent storage of those gases, including to facilitate and regulate the exploration for suitable underground geological storage formations, as part of Victoria's commitment to the reduction of atmospheric greenhouse gas emissions.

The Act of the State of Victoria, Australia provides the regulatory framework for geological storage of captured CO_2 and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- Petroleum and Geothermal Energy Regulations 2013

The regulations provide an effective and expeditious regulatory and approvals framework applicable to geothermal and gas storage activities including licence applications, environment protection, operator classification and activity notification, notice of entry on land, operational issues, reports and information.

The regulation of the State of South Australia provides the regulatory framework for geological storage of captured CO_2 and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- Greenhouse Gas Storage Act 2009

The Act is to help reduce the impact of greenhouse gas emissions on the environment principally by facilitating greenhouse gas geological storage and creating a regulatory system for the carrying out of activities.
The regulation of the State of Queensland provides the regulatory framework for geological storage of captured CO_2 and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

	There is a regulatory framework in place for sequestering of CO_2 within its jurisdiction. However no regulatory framework is noted for the offloading of captured LCO_2 from ships, although there are no prohibitive regulations.

12.7 South Korea

South Korea has the legal framework specific to the CCS regulating the activities of CO_2 capture, transport, utilisation and storage through the Carbon Neutrality Act.

12.7.1 Issues Related to International Transport of Captured CO_2

South Korea is a party to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the London Protocol and has ratified the London Protocol to the London Convention in 2009.

	There is no regulatory framework in place for international transport of captured CO_2, although there are no prohibitive regulations noted in this respect.

12.7.2 Health, Safety and Environment

Korea Occupational Safety and Health Agency (KOSHA) contributes to national economic development by keeping workers safe and making employers endeavour to prevent industrial accidents and diseases.

- Industrial Safety and Health Act

The purpose of this Act is to maintain and promote the safety and health of workers by preventing industrial accidents through establishing standards on industrial safety and health and clarifying where the responsibility lies, and by creating a comfortable working environment. The regulations align with the Globally Harmonized System of Classification and Labelling of Chemicals (GHS).

	There are no prohibitive regulations noted from the HSE perspective that could be a barrier to the offloading of captured LCO_2 from ships.

12.7.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading in Ports

- Carbon Neutrality Act

The Act mandates targets of GHG emission reduction by 40% in 2030 from the 2018 levels and consists of several policy measures to achieve carbon neutrality by 2050.
The Act involves the development of CCS as a pathway towards carbon neutrality and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- 2050 Carbon Neutrality Strategy

The carbon neutrality strategy outlines proposals in sectors such as power supply, transportation, hydrogen, and CCUS.
The policy involves the development of CCS and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- Korea Emissions Trading Scheme (K-ETS)

The Korea Emissions Trading Scheme (K-ETS) launched in 2015 as East Asia's first nationwide, mandatory ETS. It covers around 74% of South Korea's national GHG emissions and will help the country in its objective to become carbon neutral by 2050, a target embedded in the Carbon Neutrality Act.

The K-ETS covers 684 of the country's largest emitters in the power, industrial, buildings, waste, transport, and domestic aviation sectors. At least 10% of allowances must be auctioned. Free allocation is provided for EITE sectors based on production cost and trade intensity benchmarks. Since 2021, domestic financial intermediaries and other third parties have been able to participate in exchange.

	There is a regulatory framework in place covering CCS. However no regulatory framework is noted for the offloading of captured LCO_2 from ships, although there are no prohibitive regulations.

12.8 China

China does not have the legal framework specific to the CCS regulating the activities of CO_2 capture, transport, utilisation and storage, and the legal and technical aspects of CCUS projects are reliant on existing legal instruments. However, since the year 2006 the country has progressively formulated formulating policies for the development of CCUS through their 5-year plans. The latest 14th five-year plan released with goals of carbon peak in 2030 and carbon neutrality by 2060 with CCS continues to be identified as key in mitigating climate change.

12.8.1 Issues Related to International Transport of Captured CO_2

China is a party to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (London Convention) and the London Protocol.

China acceded to the London Convention in 1985 and ratified the London Protocol in 2006.

	There is no regulatory framework in place for international transport of captured CO_2, although there are no prohibitive regulations noted in this respect.

12.8.2 Health, Safety and Environment

- Technical Guideline for Environmental Risk Assessment of Carbon Dioxide Capture, Utilisation and Storage

The guideline provides the technological guidance for CCUS environmental risk assessment of carbon dioxide capture, geological utilisation and geological storage projects on land.

The policy involves the development of CCS and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

	There are no prohibitive regulations noted from the HSE perspective that could be a barrier to the offloading of captured LCO_2 from ships.

12.8.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading in Ports

- 13th Five-Year Special Program Plan for Scientific and Technological Innovation to Address Climate Change

The plan outlines a variety of key technology goals to develop greenhouse gas emissions reduction technologies in achieving large-scale CCUS.

The policy involves the development of CCS and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

- Guidelines for the Establishment of a Standard System for Carbon Peak and Carbon Neutrality

These Guidelines are formulated to accelerate the construction of a carbon peaking and carbon neutrality standard system with reasonable structure and clear hierarchy, and suitable for high-quality economic and social development.

The guideline focuses on basic universal standards, carbon emissions reduction, carbon removal, and carbon market development, and although not explicitly stated may be relevant to downstream storage capacity of LCO_2 offloaded from ships.

	There is a no regulatory framework in place covering CCS, but there is movement on the policy front. However no regulatory framework is noted for the offloading of captured LCO_2 from ships, although there are no prohibitive regulations.

12.9 Japan

Japan is in the process of developing a legal framework specific to the CCS regulating the activities of CO_2 capture, transport, utilisation and storage leaded by Ministry of Economy, Trade and Industry (METI).

Japan with the aim of leading the deployment of CCS technology in the region is reported to have submitted draft rules for CCS to Asia Zero Emission Community (AZEC) meeting held in Indonesia in June 2023. The rules are now expected to be discussed by the AZEC members and a detailed proposal will be presented in the AZEC ministerial meeting scheduled to be held in early 2024.

12.9.1 Issues Related to International Transport of Captured CO_2

- Law Relating to the Prevention of Marine Pollution and Maritime Disaster

The purpose of this Law is to prevent marine pollution and maritime disaster in order to contribute to the preservation of the marine environment and includes the CCUS permitting that is primarily focused on protecting the marine environment from any adverse impacts of sub-seabed storage activities in line with the London Convention and Protocol, rather than CCS as a low-carbon technology.

The law provides for the regulatory framework for permitting sub-seabed storage activities in line with the London Convention and Protocol and is thus relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

	The regulatory framework is under development for international transport of captured CO_2, although there are no prohibitive regulations noted in this respect.

12.9.2 Health, Safety and Environment

Japan Industrial Safety and Health Association (JISHA) is the authority in Japan occupational for safety and health standards.

- Industrial Safety and Health Law

The purpose of this Act is to secure, in conjunction with the Labor Standards Act (Act No. 49 of 1947), the safety and health of workers in workplaces, as well as to facilitate the establishment of comfortable working environment, by promoting comprehensive and systematic countermeasures concerning the prevention of industrial accidents, such as taking measures for the establishment of standards for hazard prevention, clarifying the safety and health management responsibility and the promotion of voluntary activities with a view to preventing industrial accidents

	There are no prohibitive regulations noted from the HSE perspective that could be a barrier to the offloading of captured LCO_2 from ships.

12.9.3 Policy Landscape for CCUS Pertinent to CO_2 Offloading in Ports

- CCS Long-Term Roadmap

The roadmap aims to boost the deployment of CCS technologies by targeting commercial deployment by 2030.

CCS is included in the plan as a potential decarbonization pathway for hard-to-abate industries where decarbonization through electrification or hydrogenation is not feasible, but the relevance to LCO_2 offloading from ships is not known.

- Roadmap for Carbon Recycling Technologies

The roadmap for carbon recycling technologies to specify goals, technological challenges and timeframes regarding carbon recycling technologies and accelerate innovation.

The policy refers CO_2 as a resource, separating and collecting it, and reusing it for making various products such as concrete, chemicals and fuels, and the relevance is in LCO_2 offloaded from ships treated as a resource.

- Cool Earth-Energy Innovative Technology Plan

The strategy sets out for the development of innovative technology for achieving the long-term target of halving global greenhouse gas emissions by 2050 from the current levels under Cool Earth 50.

The roadmap sets out the development of 21 selected innovative energy technology fields including CCS. The policy involves the development of CCS and is relevant to the availability of downstream storage capacity of LCO_2 offloaded from ships.

	The regulatory framework specific to CCS is under development. However, at this moment no regulatory framework for the offloading of captured LCO_2 from ships yet, although there are no prohibitive regulations.

12.10 References

[1] UNFCCC, "https://unfccc.int/topics/mitigation/workstreams/emissions-from-international-transport-bunker-fuels"

[2] IMO, "GISIS Port Reception Facility Database".

[3] GOV.UK, "The Dangerous Goods in Harbour Areas Regulations 2016 (legislation.gov.uk)".

[4] European Commission, Directorate-General for Energy, Bolscher, H., Guevara Opinska, L., Finesso, A. et al., EU regulation for the development of the market for CO_2 transport and storage, Publications Office of the European Union, 2023

[5] KEFM, "https://kefm.dk/Media/637606718216961589/Principaftale%20om%20CO2-lagring.pdf".

[6] KEFM, "https://kefm.dk/Media/637750877973046181/Aftaletekst_final.pdf".

[7] KEFM, "https://kefm.dk/Media/637914812834794479/Aftale%20om%20rammevilk%C3%A5r%20for%20CO2-lagring.pdf".

[8] KEFM, “Consolidated Act No. 1655 of 25 December 2022”.

[9] ICETRA, “https://www.icetra.is/media/english/Act-No.-119-2012-on-the-Icelandic-Transport-Authority-as-amended.pdf”.

[10] ICETRA, “https://www.icetra.is/media/english/Act-on-Maritime-Security-No.-50-2004.pdf”.

[11] “https://www.regjeringen.no/en/historical-archive/solbergs-government/Ministries/smk/Press-releases/2020/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/”.

[12] “https://www.regjeringen.no/en/historical-archive/solbergs-government/Ministries/smk/Press-releases/2020/the-government-launches-longship-for-carbon-capture-and-storage-in-norway/id2765288/”.

[13] W. &. C. LLP, Seth Kerschner, Taylor Pullins, Brittany Curcuru, White & Case “How US environmental laws and regulations affect carbon capture and storage”, May 2021.

ACKNOWLEDGEMENTS

Unlocking the carbon value chain initiative at GCMD

Project sponsor: Sanjay Kuttan
Study lead: Eng Kiong Koh
Study team members: Victor Pang, Urwah Khan (currently Advisor - Climate and Energy, UNEP Copenhagen Climate Centre)

Observers

Maritime and Port Authority of Singapore (MPA)
Port of Rotterdam (PoR)

Appointed consultant

Lloyd Register

Project sponsor: Douglas Raitt
Study Technical Head: Jose Navarro
Study lead: Brijesh Tewari
Study team members: Nelson Loo, Sun-Joo Choi, Alex Pedgrift, Yildiz Williams, Gilmark D Mello, Naroshinii A Annaselam, Manuel Dominguez Santisbon

Supporting organisation

Arup

Project sponsor: James Turley
Study lead: Mark Button
Study team members: Robert Cooke, Sinthujan Pushpakaran, Tom Phillips, Lydia Green, Ben Rigby, Andrew Horton

Study partners

Advario Asia Pacific Pte Ltd
Alfa Laval / Framo AS
Boston Consulting Group
BHP Billiton Freight Singapore Pte Ltd
bp Singapore Pte Ltd
BW Epic Kosan Maritime Pte ltd
Chevron Asia Pacific Shipping Pte Ltd
CLEOS - Olympic Shipping and Management S.A.
Emerson Asia Pacific Pte Ltd
Endress & Hauser (S.E.A) Pte Ltd
Eastern Pacific Shipping Pte Ltd
Gard P & I (Bermuda) Ltd
Hapag-Lloyd AG

ACKNOWLEDGEMENTS

Jurong Port Pte Ltd
Kawasaki Kisen Kaisha Ltd
Navigator Gas LLC
Panasia Co., Ltd
Pavilion Energy Singapore Pte Ltd
PSA Corporation Ltd
SeaTech Solutions International (S) Pte Ltd
Seatrium Ltd
Shell Eastern Trading (Pte) Ltd
Singapore Shipping Association
Singapore LNG Corporation Pte Ltd
Stena Rederi AB
Woodside Energy Limited

Industry and Consultation Alignment Panel (iCAP) members

Equatorial Marine Fuel Management Services Pte Ltd
Gas Ancillary Services Pte Ltd
Lattice International AS
Longitude Engineering Pte Ltd
MISC Berhad
Mitsui O.S.K Lines, Ltd
National Metrology Centre (NMC), A*STAR Research Entities
Sinotech CCS Co., Ltd
Wah Kwong Maritime Transport Holdings Ltd
Yara International ASA
ZICOM Pte Ltd

ABOUT

the Global Centre for Maritime Decarbonisation

The Global Centre for Maritime Decarbonisation (GCMD) was established as a non-profit organisation on 1 August 2021 with a mission to support the decarbonisation of the maritime industry by shaping standards, deploying solutions, financing projects, and fostering collaboration across sectors.

Founded by six industry partners namely BHP, BW Group, Eastern Pacific Shipping, Foundation Det Norske Veritas, Ocean Network Express and Seatrium (formerly Sembcorp Marine), GCMD also receives funding from the Maritime and Port Authority of Singapore (MPA) for qualifying research and development programmes and projects. To-date, over 100 centre- and project-level partners have joined GCMD contributing funds, expertise and in-kind support to accelerate the deployment of scalable low-carbon technologies and lowering adoption barriers.

Since its establishment, GCMD has launched four key initiatives to close technical and operational gaps in: deploying ammonia as a marine fuel, developing an assurance framework for drop-in green fuels, unlocking the carbon value chain through shipboard carbon capture and articulating the value chain of captured carbon dioxide as well as closing the data-financing gap to widen the adoption of energy efficiency technologies.

GCMD is strategically located in Singapore, the world's largest bunkering hub and second largest container port.

Contact us

projects@gcformd.org

Global Centre for Maritime Decarbonisation (GCMD)

www.gcformd.org