GIIGNL
International Group Of Liquefied Natural Gas Importers

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GIIGNL/TSG: Task Force LCO_2 Terminaling

Combining LNG receiving and CO_2 liquefaction terminals: Challenges and synergies

Content

1. Introduction

Carbon Capture and Storage (CCS) is critical for achieving the objectives of net zero emissions. Addressing the development of each component of the CCS chain is key to accelerating carbon dioxide (CO_2) network deployment. Nevertheless, a gap exists between the growing need for CO_2 infrastructure and project development, mainly due to costs and technical challenges.

Within the CCS chain, liquid CO_2 (LCO_2) export terminals are necessary to support ship transport over long distances and connect capture facilities and CO_2 hubs with offshore storage reservoirs. In this context, CO_2 liquefaction performed in export terminals close to Liquefied Natural Gas (LNG) receiving ones allows the recovery of cold energy from LNG. It can help to reduce emissions and enhance the energy efficiency of the CO_2 liquefaction process.

1.1. Scope and purpose of the document

The purpose of this document is to evaluate the challenges and synergies of integrating LCO_2 export terminals in existing LNG receiving facilities. This evaluation has been carried out by the Technical Study Group Task Force of the International Group of Liquefied Natural Gas Importers (GIIGNL).

The study assesses the risks associated with CO_2 in both gaseous and liquid phases, along with their mitigation strategies. It explores the synergies and interfaces between LNG and CO_2, detailing a scheme for an integrated terminal, including general design, equipment, and process considerations. Additionally, the study examines the risks and safety hazards arising from the interactions and co-location of these terminals. Finally, the study aims to highlight the main impacts on the operation of LNG terminals.

1.2. Organization of the Study

The study was conducted by leading expert representatives from thirteen Member Companies of GIIGNL as follows:

elengy, Lab Crigen (Research & Innovation), bp, dunkerque LNG (fluxys), equinor, fluxys, MOL, nationalgrid, OSAKA GAS, SEMPRA INFRASTRUCTURE, Shell, TOKYO GAS, TotalEnergies

The composition of the Technical Study Group Task Force which participated in this report and met regularly in the process of the evaluation of the information is as follows:

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The coordination team expresses its sincere gratitude to the participants for their valuable contributions. Based on their expertise, the participants provided insights and input on key subjects within the task force's scope. Other members subsequently offered suggestions where necessary, ensuring a collaborative effort. Special thanks are owed to Dunkerque LNG, TotalEnergies, Shell, Sempra Infrastructure, BP and Osaka Gas teams, for their specific drafting, with additional thanks to Richard Ellis, for his review and rigorous work in refining the final edition of this report.

2. (L)CO_2 product

2.1. Product characteristics of CO_2

CO_2 is a colourless, odourless gas that exists naturally in the atmosphere at approximately 0.04% concentration. It is commonly used in industries such as food processing, beverage production, and carbon capture and storage (CCS) technologies. When cooled and compressed, CO_2 transitions to a liquid state, which is used in various industrial and scientific applications. The key properties of CO_2 are listed in Table 1.

Table 1 – Key properties of CO_2

Chemical Formula	CO_2
Physical State	Gas in atmospheric conditions, liquid when pressurized and cooled. At atmospheric pressure, CO_2 is not a liquid at any temperature; it sublimates directly from a solid to a gas at -78.5°C. CO_2 becomes a liquid only under conditions where the pressure is above 5.18 bar (its triple point pressure), and the temperature is between -56.6°C and 31.1°C (its critical temperature). Refer to CO_2 phase diagram in part 3.1.3.1.
Density	Heavier than air in gaseous form. In liquid form, its density increases significantly.
Solubility	Highly soluble in water, forming carbonic acid.
Toxicity	Non-toxic in low concentrations, but potentially harmful at elevated levels.
Freezing and boiling Points	Sublimes directly from solid to gas at -78.5°C under atmospheric pressure.

2.2. CO_2 risk assessment & mitigations

2.2.1. Risks associated with liquid and gaseous CO_2

Despite its widespread use, CO_2 poses several hazards, particularly in liquid form, due to its storage and handling requirements. These risks, described in Table 2, arise from its physical and chemical properties, and its behaviour under varying conditions.

Table 2 – Key Risks and Mitigation Measures

Risk	Description	Potential impact	Mitigation measures	Source	LNG terminal & area considerations
Asphyxiation	CO_2 displaces oxygen in low-lying or confined spaces.	Dizziness, unconsciousness, or death due to oxygen deprivation.	• Ensure proper ventilation, • Install CO_2 detectors and alarms, • Restrict access to confined spaces.	HSE - General hazards of Carbon Dioxide [1]	Areas where connections/transfers are made: • Jetty Areas • Truck Loading • Maintenance activities
High concentration exposure	Exposure to elevated levels of CO_2 can affect human health.	Headaches, dizziness, confusion, and loss of consciousness.	• Monitor workplace CO_2 levels, • Adhere to exposure limits, • Implement safety protocols.	HSE - General hazards of Carbon Dioxide [1]	As above
High-pressure energy release	Rapid expansion of gaseous and/or liquid CO_2 during accidental release.	Equipment damage.	• Regular inspections, • Use of pressure relief devices, • Training personnel on safe handling.	AIGA - Safe Handling of Liquid Carbon Dioxide Containers [2]	Specific to CO_2 operations: • Collateral damage to LNG equipment and systems
Cryogenic burns and frostbite	Direct contact with liquid CO_2 at cryogenic temperatures (as low as -56.6°C).	Severe tissue damage, frostbite, and potential nerve damage.	• Personal protective equipment (PPE) including cryogenic gloves and face shields, • Avoid direct contact, • Proper training on cryogenic safety.	BCGA CP26 - Bulk Liquid Carbon Dioxide Storage [3]	Similar to LNG hazards: • Transfer areas. • Maintenance activities
Corrosion	CO_2 forms carbonic acid in presence of water, leading to corrosion.	Equipment damage, leaks, environmental contamination.	• Use corrosion-resistant materials, • Control moisture,	IPCC - Transport of CO_2 [4]	Water ingress at transfer areas, jetty operations, improper isolation, and purging. Potential leakage to atmosphere in

			• Implement maintenance schedules.		confined areas causing corrosion on supports, exterior of pipes.
Ductile running or brittle fracture	High-pressure pipelines can experience rapid crack propagation.	Pipeline damage, large-scale CO_2 release.	• Design pipelines for decompression resistance, • Use appropriate materials, • Conduct integrity assessments.	Penspen - Assessing Safety Risks for CO_2 Pipelines [5]	Strict adherence to codes and standards specific to CO_2 system design and process requirements. Areas where mixing of CO_2 and LNG design standards is required should be rigorously scrutinized and subject to full hazard assessment.
Accumulation in low-lying areas	Natural CO_2 emissions collect in depressions (Mazuku phenomenon).	Suffocation risks to humans and animals in affected areas.	• Monitor CO_2 levels, • Restrict access to vulnerable areas, • Install warning systems.	Wikipedia - Mazuku [6]	LNG Impoundment areas, sumps, highly congested equipment areas.

2.2.2. Addressing CO_2 Risks

Possible actions to address CO_2 risks are presented in Table 3.

Table 3 – Actions to address CO_2 risks

Action	Detail	LNG terminal considerations
Education and training	Ensuring personnel are trained in the properties and risks of gaseous and liquid CO_2.	HAZOP proposed integrated facilities as a whole. Special considerations: Identification of areas where CO_2 can accumulate in LNG process areas; Potential CO_2 /LNG comingling due to operating errors, interruptions, equipment failure. Revise Control of Work procedures to include added hazards to personnel. Update all facility training to incorporate hazards of CO_2 and associated operations. Identify specific, existing operating and maintenance procedures and follow Management of Change (MOC) processes to incorporate identified hazards.

Infrastructure and design	Implementing systems designed for safe storage and handling of liquid CO_2, including corrosion-resistant materials, pressure relief devices, appropriate hazard detection for potential CO_2 releases and accumulation of CO_2 in low-lying areas.	Review of LNG plant impoundment, collection sumps, runoff areas and other low-lying areas where CO_2 may accumulate. Consider detection and annunciation systems as well as passive mitigations, such as redesign/relocation of equipment, and developing active mitigations where necessary.
Monitoring and detection	Using advanced CO_2 monitoring and detection systems in workplaces and storage facilities.	Integration of CO_2 specific hazard monitoring directly into plant hazard monitoring system, including distinct and separate alarm annunciation in the field and control room/control monitoring areas. LNG & CO_2 facilities exchanging heat or material streams should have integrated risk and hazard communication systems.
Regular maintenance	Conducting routine inspections and maintenance of storage vessels, pipelines, and safety equipment.	Simultaneous Operations (SIMOPS) considerations for all maintenance, e.g., risk assessment required.
Emergency Response Planning	Establishing and practicing emergency response protocols for potential CO_2-related incidents.	Update all relevant LNG Terminal Emergency Response documents and tools.

The unique properties of CO_2, while beneficial in various applications, present specific risks that require careful management. By following established guidelines and implementing robust safety measures, industries can effectively mitigate these risks and ensure the safe handling, processing, and storage of both gaseous and liquid CO_2.

2.2.3. Risks and mitigations specific to gaseous CO2

Pipelines transporting CO_2 for liquefaction from other facilities typically carry CO_2 with specific composition requirements to ensure operational safety and efficiency. The composition must meet strict purity standards to prevent risks associated with impurities that could affect phase behaviour, pipeline integrity, and downstream processes. A well-designed specification will set facility needs and determine requirements for onsite pretreatment. Onsite CO_2 sampling/monitoring to confirm quality entering the terminal should be considered.

Table 4 shows the typical gaseous CO_2 composition and Table 5 the importance of composition control.

Table 4 – Typical composition

CO_2 purity	Generally, above 95 – 99% to ensure efficient compression and liquefaction processes.
Water content	Extremely low to avoid formation of hydrates or carbonic acid, which can cause corrosion.

Non-condensable Gases	Includes minimal levels of oxygen, nitrogen, and argon to prevent pressure issues and maintain system integrity.
Hydrocarbons	Strictly controlled to avoid operational challenges and safety risks.
Sulphur compounds	Hydrogen sulphide and other sulphur compounds must be reduced to negligible levels to prevent toxicity and corrosion.
Nitrogen oxides	Nitrogen oxides must be reduced to negligible levels to prevent toxicity and corrosion.

Table 5 - Importance of composition control

Prevention of corrosion	Controlling water and sulphur compound levels minimizes the formation of corrosive substances.
Efficiency in liquefaction	High purity CO_2 ensures effective cooling and compression during liquefaction processes.
Pipeline integrity	Maintaining composition standards reduces risks of hydrate formation and material degradation in pipelines.
Operational safety	Adherence to composition standards mitigates risks related to toxicity, phase instability, and equipment failure.

CCS projects can be open-sourced, meaning the CO_2 to be stored can come from a wide portfolio of emitters. However, there is currently no established standard for CO_2 specification in either gaseous or liquid transport and pipeline operators set their own requirements for the composition of CO_2 entering their infrastructure. These specifications vary across ongoing CO_2 carbon capture and storage (CCS) projects, depending on project-specific conditions, infrastructure design, and assumptions. Examples of pipeline specification include those set by Fluxys, Porthos, and Aramis. As research and experimental testing continue, these specifications are expected to evolve.

2.2.4 Risks and mitigations specific to liquid CO_2

Table 7 provides an overview of the risks and mitigations specifically linked to liquid CO_2.

Table 6 – Risks and mitigations linked to liquid CO_2

Risk Category	Hazards	Mitigation measures	LNG terminal considerations
Cryogenic temperatures	LCO_2 is transported at cryogenic temperatures, ranging between -20°C and -50°C. At low pressure (LP), the temperature is at around -50°C, posing risks of frostbite and cryogenic	Use of thermal insulation and protective clothing for personnel. Regular maintenance to ensure equipment integrity under cryogenic conditions.	Like LNG, pipe covering and/or labelling conventions should be clearly communicated and strictly followed to reduce misidentification of piping systems during operations and maintenance.

	burns in the event of leaks or accidental contact. Low temperatures can embrittle materials, increasing the risk of structural failure. At medium pressure (MP), CO_2 is transported at around -30°C, this enables the selection of Low Temperature Carbon Steel (LTCS).		
Pressurization and phase change risks	Stored at pressures ranging between 7 and 19 barg (namely 7 barg in LP and 15 barg in MP form). Sudden pressure drops can cause rapid expansion and explosive decompression. Phase changes may fragment pipelines and containers.	Incorporation of pressure-relief systems and safety valves. Use of materials in pipelines and storage tanks rated for the specific pressure regime.	Consider differences in relief characteristics between LNG and CO_2 – CO_2 phase change could cause blockage and plug relief devices.
Toxicity and asphyxiation	CO_2 is heavier than air, and leaks may displace oxygen, creating asphyxiation risks in low-lying areas. Trace impurities like H_2S and NO_x are toxic and hazardous.	Installation of CO_2 and oxygen sensors in storage and operational areas. Development of emergency evacuation procedures and regular safety drills.	Develop a "map" of areas that may become hazardous locations resulting from CO_2 releases.
Corrosion and material	Impurities like H_2O, SOx, NOx, and H2S can react to form acids, accelerating corrosion.	Use of corrosion-resistant materials, such as stainless steel or special alloys, for all equipment or use less corrosion-resistant materials (LTCS) and rely on stringent CO_2 quality specification (Northern Lights project case).	Testing the stream should be considered. Pretreatment requirements should be clearly understood, and limits adhered to.
Degradation	Trace mercury can amalgamate with metals, causing material degradation.	Regular monitoring and maintenance to detect and address	Scavenger bed if aluminium equipment.

		early signs of corrosion.	
Environmental risks	Large-scale releases could lead to greenhouse gas impacts to the environment.	Comprehensive leak detection systems to identify and mitigate spills promptly.	Adequate leak detection to minimize the risk from large releases. Consider compartmentalization of large inventory pipework via use of emergency isolation valves.

As mentioned in 2.2.3, there is no current standard for CO_2 specification and operators will set the specifications for LCO_2 infrastructure. CO_2 composition requirements for projects such as Northern Lights and Aramis are defined to minimize safety risks during transport and storage, mitigate corrosion issues, and account for impurities present across the industry segments utilizing these facilities.

CCS design choices—such as purification processes and material selection—are closely linked to specification. As specifications continue to evolve, projects like Northern Lights serve as examples of this evolution, it initially established LCO_2 specifications in 2021, which were updated in 2024 to become even more stringent.

These specifications include maximum allowable concentrations of impurities such as water, nitrogen oxides (NOx), sulphur oxides (SOx), hydrogen sulphide (H2S) and mercury (Hg).

Ensuring adherence to the selected specifications, combined with robust monitoring and emergency response protocols, is essential for mitigating the operational, environmental, and safety hazards associated with liquid CO_2. However, the challenge lies in ensuring effective purification technologies, monitoring systems, and precise measuring techniques, especially given that some component specifications are at extremely low ppm levels.

3. Synergies and interfaces between LNG receiving terminal and LCO_2 export terminal

3.1. Operational requirements for fully integrated CO_2 liquefaction on an LNG terminal

3.1.1. Cold synergy

When considering the use of CO_2 for CCS, it is necessary to transport captured CO_2 from the emission source to the storage site. If the CO_2 storage site is offshore, then transportation can be by either ship or pipeline. However, the longer the distance, the more advantageous transportation by ship.

It is possible to transport CO_2 on a ship as a gas at room temperature. However, it requires high pressures (>35 barg). Furthermore, as injection into the underground storage site is more efficient in supercritical state, it is necessary to liquefy CO_2 at some point on the CCS chain. For CCS projects using ship transportation, it is considered rational to liquefy CO_2 near the emission source, transport it, and inject it into the ground. Liquefaction can either be done directly after capture at the emission site or in a hub (export terminal) where CO_2 from multiple emission sources is aggregated and liquefied at a unique location before export. Most schemes currently under consideration are based on transporting CO_2 as a liquid at pressures between 7 and 19 barg and temperatures between -20°C to -50°C.

LNG receiving terminals produce natural gas by vaporizing LNG, a process generating cold energy that could potentially be used in the CO_2 liquefaction process for CCS. The available cold energy, when vaporizing LNG and heating natural gas to 0°C, ranges around 230 kWh/tonne of LNG at normal pressure conditions. The amount of energy required to liquefy CO_2 depends on the CO_2 inlet conditions and the desired final conditions, but it is significant (around 100 kWh/tonne of CO_2 for pure CO_2 at 1 bara and liquefied at 20 bara). This leads to substantial OPEX and CO_2 emissions. Therefore, utilizing "free" cold energy from LNG for CO_2 liquefaction is an opportunity to reduce energy consumption and, as a result, the process OPEX. This synergy is of great significance from an environmental and economic perspective.

If the incoming CO_2 is delivered at the battery limit of the terminal at a pressure close to its future storage pressure under liquid form, it is estimated that the liquefaction of 1 kg of CO_2 requires the vaporization of 0.7 to 0.8 kg of LNG. If the incoming CO_2 is at much higher pressure, for instance above the critical point in the dense phase, the expansion of the CO_2 to the storage pressure will have a cooling effect leading to a reduced LNG to CO_2 ratio of approximately 0.3 kg of LNG vaporized per kg of CO_2 liquefied.

3.1.2. Description of an integrated LCO_2 terminal in an LNG import facility

Figure 1 presents an example of a terminal with LNG cold recovery for cryogenic CO_2 liquefaction.

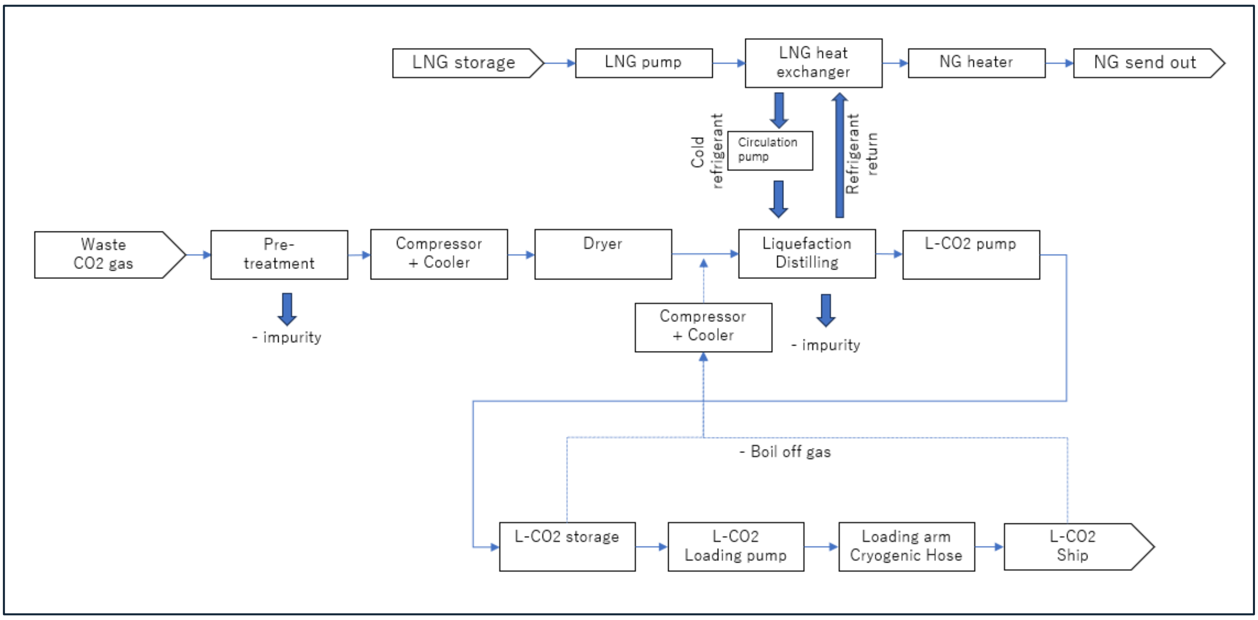


Figure 1 – Example of LNG cryogenic cold utilization for CO_2 liquefaction block diagram

The terminal includes the following steps:

- CO_2 transport from the emission source: gaseous CO_2 is transported from each source using pipelines, etc.
- Pretreatment: Impurities in the CO_2 are removed by pretreatment equipment.
- Compression: CO_2 is compressed to high pressure leading to an increase of temperature. The hot CO_2 is then cooled to approximately ambient temperature with a cooler.
- Liquefaction: The CO_2 is then further cooled and liquefied using a refrigeration process. Power for the refrigeration process is typically provided by electricity, but this could be supplemented or replaced by waste cold heat from LNG.
- Transfer & storage: The liquefied CO_2 is transferred to a low-temperature storage tank and stored.
- Loading: The stored CO_2 is loaded onto a LCO_2 carrier using a LCO_2 loading pump.
- Vapor Return management: Vapor return collected during cargo handling is mixed with boil-off gas from storage tanks and returned to the pretreatment or liquefaction facility.

Table 9 summarizes the main LCO_2 loading terminal facilities with their associated equipment.

Table 7 – Main facilities at a LCO_2 loading terminal

	Main facilities	**Remarks**
1	CO_2 receiving facilities	Metering, analyser
2	Pretreatment facilities	Removal of impurities
3	Liquefaction and distillation facilities	Compressors, liquefaction and refining equipment, chillers, analysers
4	LCO_2 storage facilities	Storage of liquefied carbon dioxide
5	LCO_2 loading pumps	Pumps for transferring LCO_2 from storage facilities to transport vessels

6	Loading arms or cryogenic hoses	Ship connection facilities for cargo handling
7	Utilities	Power, instrumentation, control and safety instrumented systems, water, CO_2, etc.
8	Control room	

- LNG receiving terminals are usually located on the coast near a large energy consumption area. In addition, since the CO_2 collecting point must be located close to industrial areas where substantial amounts of energy are consumed, there is a high possibility that they can be located adjacent to each other.

Table 10 highlights common facilities between LCO_2 and LNG sites and the possible synergies.

Table 8 – Synergy between CCS loading terminal and LNG receiving terminal facilities

	Facilities	**Notes**
1	Berth	In terms of the berth design, the specific gravity of LCO_2 is around 1, which is about twice that of LNG, generally between 0.42 and 0.49. There are common points in LNG and LCO_2 handling as low-temperature liquefied gases.
2	Vaporization and liquefaction energy	LNG waste cold heat is used for CO_2 liquefaction and purification. Cold energy from LNG can be recovered by an intermediate fluid, the cold is then used to liquefy CO_2 in the LCO_2 facilities
3	Utilities	Electricity, instrumentation, control and safety instrumented systems, water, instrument, and service air, etc.
4	Control room, operator, etc.	There are common points in handling liquefied gases.

3.1.3. Design best practices, applicable codes and standards

The following sections describe general design, equipment, and flexibility considerations as well as codes and standards.

3.1.3.1. General design considerations

CO_2 liquefaction is the process of cooling an incoming stream of gaseous CO_2 down to a temperature where it becomes a liquid. The phase diagram of pure CO_2 in Figure 2 illustrates the pressure and temperature conditions to which the CO_2 stream must be brought to be liquefied before being stored and exported under its liquid form.

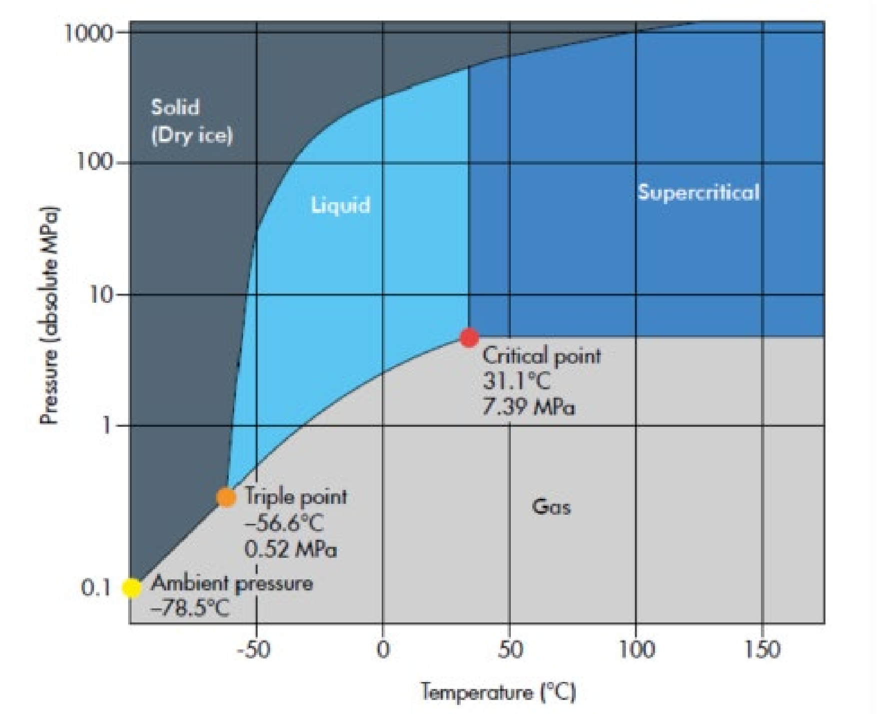


Figure 2 – Phase diagram of pure CO_2 (extracted from SIGTTO paper)

With regards to the temperature, these conditions are between the triple point (-56.6°C) and the critical point (31.1 °C). The triple point (-56.6°C, 5.18 bara) is the temperature and pressure at which solid, liquid and vapor phases of the CO_2 can coexist in equilibrium.

From the phase diagram, it is evident that liquefied CO_2 cannot be produced or stored at pressures below 5.18 bara to avoid formation of solid CO_2 also called "dry Ice."

The phase diagram also shows that at no point in the process of liquefaction, should the temperature go below liquid/solid transition line. This is particularly important when considering the synergy of using the cold energy available from the LNG during its vaporization. The LNG being pumped from the storage tanks at about -162°C, there is an obvious risk of creating dry ice in case of direct exchange between the LNG and the CO_2.

This risk can be mitigated by using an intermediate fluid, which will not freeze over the range of temperature curves, to transfer the cold energy from the LNG to the CO_2. The choice of the intermediate fluid (e.g., ethane, propane, pentane or ammonia) depends on several aspects, such as the CO_2 liquefaction conditions, the cold recovery integration heat exchanger design, and safety considerations.

Safety studies conducted on the new facilities and their integration within the LNG receiving terminal must take into account the risks arising from the introduction of the intermediate fluid along with those associated with the introduction of CO_2 stream. These include, but are not limited to, the risk of boiling liquid expanding vapor explosion (BLEVE) in storage vessels, and the risk of flammable gas clouds that are heavier than air in the event of a leak.

The LCO_2 shipping industry is under development and a wide range of pressure/temperature combinations are under consideration for the storage tanks of the LCO_2 at boiling point conditions.

These ranges are from what is known as LP (about 7 barg and -46°C) to what is known as MP (about 15 barg and -26°C)

The operating conditions (pressure and temperature) of the CO_2 liquefaction process and of the terminal storage tanks should preferably be aligned with the ship's storage conditions. Having the same pressure and temperature conditions on both sides eases the transfer from the terminal to the ships, the pressure management, and the boil off management during the loading operation. Different pressure and temperature conditions could be considered (see section 3.2.3.2.) but specific design adjustments should then be made. Despite this, most ships will not have a liquefaction skid on board and CO_2 pressure will increase during the ballast voyage, leading to a requirement to manage pressure by depressurizing the ship at the loading port.

The incoming stream of gaseous CO_2 can arrive purified enough to be at the LCO_2 shipping specifications. In this case, the process will consist only of the liquefaction of the CO_2. Nevertheless, the quality of the vapor return is also a crucial factor and needs to be analysed to ensure that it is not out-of-specification due to the presence of some components highly concentrated in the vapor phase.

On the other hand, if the incoming stream of gaseous CO_2 arrives with higher impurities content than the shipping specifications, additional steps of treatment are required such as a fractionation column which allows the light components (volatiles, non-condensable, etc.) to be removed down to the required specification. Choosing a correct sequence of purification is key to avoiding additional contamination of CO_2 during the process. Thus, liquefaction and treatment become more complex with more energy integration required to reach the targeted Key Performance Indicators (KPIs) such as:

- CO_2 recovery rate: this is the amount of CO_2 that is liquefied, stored, and exported divided by the amount of CO_2 present in the incoming CO_2 stream. The CO_2 not exported is lost with the vented non-condensable and volatiles,
- LCO_2 purity,
- Specific power consumption of the CO_2 liquefaction process (e.g., in kWh/tonne of LCO_2),
- The ratio of LNG to CO_2: this is the quantity of vaporized LNG required to liquefy a certain amount of CO_2.

Since LCO_2 is being stored at its vapor pressure, the heat-in leaks in the storage and loading systems lead to boil-off generation. Light components vaporize preferentially and concentrate in the vapor phase forming the boil-off gas (BOG).

The boil-off gas can be:

- Recompressed by boil-off compressor to be sent back to the liquefaction system where it is reliquefied with the incoming stream of gaseous CO_2.
- Vented to the atmosphere: depending on the composition of the incoming stream of CO_2, the boil-off stream could be totally, or partially vented to get rid of volatiles and non-condensable that could prevent the LCO_2 from being at the required shipping specification. The proper ratio between boil-off to be recycled for reliquefication and vented boil-off should be assessed to limit the CO_2 losses in vented stream to their minimum while reaching the LCO_2 specifications. However, it is expected that the quantity of CO_2 vented will be low as volatile and non-condensable components should be limited by a proper definition of the specification of the CO_2 entering the terminal. The vent to the atmosphere should be easily manageable with a vent elevation high enough to allow a proper dispersion to avoid impact on terminal's personal.

Regarding the flexibility with the range of pressure supplies, the CO_2 cooling requirements vary with the pressure. If the design of the CO_2 liquefaction unit is flexible and modular enough to cope with these two ranges of supply, the LNG vaporization unit design should anticipate the variation of cooling demand from one to another supply/operating mode.

3.1.3.2. Equipment design considerations

- Material selection

Direct heat integration may induce not only operational constraints but also material selection constraints (LNG service at -160°C)/CO_2 service ranging from -20°C to -50°C) with complex and onerous equipment and piping (heat exchangers, valves, and interconnecting lines). The alternative is to adopt an intermediate cooling loop.

Material selection of new equipment and piping should be made carefully considering:

- The minimum design metal temperature and the temperature of the different fluids,
- Risks of corrosion associated with the presence of impurities in the CO_2.

- Safety

The design of the heat integration system impacts the area classification status (for example by introducing LNG piping in the CO_2 unit) as well as the fire zones definition. For example, when adding an intermediate loop with three mediums (LNG/CO_2 /intermediate fluid), the risk of leaks must be evaluated.

3.1.3.3. Codes, standards, and regulations

Cold integration in LNG receiving terminals with CO_2 liquefaction is new and hence, international design codes and standards are not specifically developed for such new facilities.

However, such integration will interface two types of facilities that have their own international design codes and standards developed independently:

- The LNG receiving terminal with the unloading and storage system and the regasification and export facilities.
- The CO_2 export terminal with the liquefaction including possible pre- and post-treatment, the storage and loading system.

The design of the new facilities will then be subject to a mix of codes and standards from both facilities.

While codes and standards applicable to the LNG receiving terminals are well known by the LNG industry and will not be listed in this report, large-scale Carbon Capture and Storage (CCS) projects are still relatively new and hence international design codes and standards are not well developed.

Here below is a list of Technical Reports (TR), codes and standards related to the CCS industry.

- ISO/TR 27912: Carbon dioxide capture - Carbon dioxide capture systems, technologies and processes
- ISO 27913:2024: Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems
- ISO/TR 27915: Carbon dioxide capture, transportation and geological storage —Quantification and verification
- ISO/TR 27918:2018: Lifecycle risk management for integrated CCS projects
- ISO/DIS 27920: Carbon dioxide capture, transportation and geological storage (CCS)—Quantification and Verification
- ISO/TR 27921: Carbon dioxide capture, transportation, and geological storage — Cross Cutting Issues — CO_2 stream composition

Additional guidance can be taken from industry research reports and studies undertaken into CCS operations. Of relevance are:

- Plant design and assessment guidance issued by the Energy Institute: “Good plant design and operation for onshore carbon capture installations and onshore pipelines,” Energy Institute, September 2010
- European Industrial Gases Association (EIGA) Doc 66/22: “Refrigerated Carbon Dioxide Storage at Users’ Premises” [7]

- The UK Health and Safety Executive: "Assessment of the major hazard potential of carbon dioxide (CO_2)" [8]
- The Wood PLC Guidelines: "Industry Guidelines for Setting the CO_2 Specification in CCS Chains" [9]

For brownfield projects with the integration of new facilities to liquefy CO_2 on an existing LNG receiving terminal, the codes, standards and regulations already in force for the existing facilities shall apply and be complemented by additional codes, standards and regulations associated with the new activity of CO_2 liquefaction, storage and loading. The order of precedence shall be defined at the design stage between the following:

- Government Regulations and Statutory Provisions
- Owner Standard Specifications and Standards
- Country and International Codes and Standards
- Project Equipment Specifications and Datasheets
- Project Standard Specifications

As a minimum, all Statutory and Government Regulations shall be followed. However, if the project-specific standards and specifications require a higher level of safety or integrity than Statutory or Government Regulations require, they shall take precedence over Government Regulations or Statutory Provisions.

3.1.3.4. Process flexibility and back-up

As mentioned in previous sections, the ratio of LNG to CO_2 for its liquefaction depends on the pressure and CO_2 inlet conditions at the battery limit of the terminal, ranging from 0.3 to over 0.8 kg LNG per kg of liquefied CO_2.

Therefore, the instantaneous capacity of CO_2 liquefaction using the cold energy from the LNG vaporization depends on the instantaneous rate of exported gas from the regasification terminal, i.e., the send-out. However, the send-out of the terminal is not constant since it varies throughout the year following the gas network nomination.

All regasification terminals are designed to operate between a minimum and a maximum send-out. Zero send-out mode is even possible during some periods. It is quite unlikely that the stream of incoming CO_2 to the terminal will follow the same variability as the send-out one. Therefore, considering the large range of operating modes on the LNG side, it seems necessary, for the availability purpose of the CO_2 liquefaction, to consider a design allowing it to operate with or without the cold integration between the vaporization of the LNG and the liquefaction of the CO_2. Again, this might represent some additional challenges from an operational standpoint. Indeed, it is quite easy for a terminal to switch from zero send-out to full send-out and revert. Conversely, switching from one mode to another (and reverting) in the case of a backup cold cycle might be more complex.

This design flexibility depends on the:

- The range of the terminal's send-out flowrate. It would be the terminal owner's and/or capacity holders' decision to accept modification of this range, in particular the minimum send-out, to accommodate the range of CO_2 liquefaction capacity selected,
- The required CO_2 liquefaction capacity,
- The CO_2 liquefaction targeted availability and the ability for the CO_2 emitters to adjust the CO_2 stream to the terminal.

The CO_2 to be liquefied will be more likely from diverse sources of supply. Its flow will depend on the availability of these different sources but also that of the CO_2 liquefaction unit itself. Any variability (in quantity or quality) in the CO_2 to be liquefied may impact the performances of the LNG vaporization unit. To mitigate its potential loss of performances, in case of CO_2 side variability, the LNG vaporization unit shall integrate a back-up heating mean (to avoid modifying the LNG flow for example).

The CCS industry being quite new and in expansion, the synergies between regasification terminals and liquefaction of CO_2 may expand with time. This may require considering phasing in design of the new LCO_2 facilities.

3.2. Specific risks and safety considerations

3.2.1. Risks induced by LCO_2 and LNG co-location

Synergies between the LCO_2 and the LNG terminals and the processes involved will impact safety measures and decisions compared to a dedicated LNG facility. Some examples already mentioned before or later in this report are as follows:

- Safety hazards: Once LNG vaporizes, it becomes flammable. Explosive atmosphere zoning (ATEX) must be considered and shared areas might contain specific CO_2 equipment. Even if CO_2 is not flammable, by sharing location, additional costs in CO_2 to comply with ATEX classification zone safety requirements will appear. In addition, CO_2 can cause asphyxiation. The proximity of both substances could complicate emergency response efforts, especially if both are released simultaneously. By utilizing cold energy from LNG in the CO_2 liquefaction using an intermediate fluid, the additional risks of three fluids must be analysed and mitigated (risk of leaks, inflammable fluids, etc.). Impurities found in CO_2 can lead to acid formation and corrosion, especially with the presence of components such as NOx, H2S and water. Therefore, equipment damage and possible leakages are also additional risks to consider.
- Thermodynamic properties: LCO_2 has unique thermodynamic properties and behaviour. It requires specific handling and storage conditions. Any deviation from these conditions could lead to operational issues, such as dry ice formation, as detailed above. In addition, similarly to LNG, LCO_2 produces boil-off gas during its storage and transportation. An excess of boil-off gas generation, if not well managed, can lead to pressure rise, venting and structural damage.
- Process and operational complexity: Both terminals' integration could also introduce additional complexity, requiring additional training to handle both fluids. When LNG cold is used to liquefy CO_2, the availability of LNG is an important parameter. Indeed, a cold backup cycle is mandatory to ensure continuous CO_2 liquefaction even while the LNG terminal is not injecting gas to the gas network. Another challenge of these synergies between both fluids is the sharing of loading facilities. For instance, carrier design is not similar between LNG and LCO_2. The latest requires larger drafts and different sizes of manifolds for instance (more details given in part 3.3).
- Environmental impact: Both LNG and LCO_2 have a significant footprint. Both facilities brought also their risk of methane and CO_2 emissions due to process, emergency responses or leakage.
- Regulatory compliance: Ensuring both terminals meet their respective safety, and environmental regulations can be challenging. Existing safety measures designed for flammable cargo may not be fully effective for LCO_2, necessitating a specific approach to identify and mitigate risks specific to projects.

3.2.2. Safety hazards: Similarities and differences in emergency procedures

When comparing the emergency procedures for LNG and LCO_2 terminals, there are both similarities and differences due to the distinct properties and hazards associated with each substance.

The similarities are presented below:

- Emergency Response Plans: Both types of terminals require comprehensive emergency response plans that include procedures for handling spills, leaks, and other emergencies.
- Safety Training: Personnel at both LNG and LCO_2 terminals must undergo rigorous safety training to handle emergencies effectively.

- Monitoring Systems: Both terminals use advanced monitoring systems to detect leaks and other hazardous conditions. These systems often include gas detectors, alarms, and surveillance cameras.
- Evacuation Procedures: Both LNG and LCO_2 terminals require well-defined evacuation procedures to ensure the safety of personnel in case of an emergency.
- Coordination with Local Authorities: Both types of terminals coordinate with local emergency services and authorities to ensure a prompt and effective response to any incident.

Regarding the differences, one can include:

- Nature of Hazards:
  - LNG: The primary hazards include flammability and explosion risks. LNG is highly flammable, and a leak can lead to a fire or explosion if it encounters an ignition source.
  - LCO_2: The main hazards are asphyxiation and pressure-related incidents. LCO_2 is not flammable, but it can displace oxygen in the air, leading to asphyxiation. Additionally, rapid release of CO_2 can cause pressure build-up and potential ruptures.
- Fire Suppression:
  - LNG: Fire suppression systems at LNG terminals are designed to handle flammable gas fires. These systems often include water deluge systems, foam, and dry chemical extinguishers.
  - LCO_2: Fire suppression is less of a concern for LCO_2 terminals since CO_2 is not flammable. However, systems are in place to manage pressure and prevent ruptures.
- Handling Spills:
  - LNG: Spills are managed by isolating the leak, using water sprays to disperse vapor, and preventing ignition sources.
  - LCO_2: Spills are managed by ventilating the area to disperse CO_2 and prevent asphyxiation. Water sprays are avoided as they can cause freeze-plugging of safety relief devices.
- Personal Protective Equipment (PPE):
  - LNG: PPE includes flame-resistant clothing, thermal protection, and breathing apparatus to protect against fire and cold burns.
  - LCO_2: PPE includes thermal protection and breathing apparatus to protect against cold burns and asphyxiation.
- Regulatory Compliance:
  - LNG: Compliance with regulations focuses on flammability and explosion prevention.
  - LCO_2: Compliance focuses on preventing asphyxiation and managing pressure safely.

3.2.3. Thermodynamic and process additional risks

This section examines the process-related additional risks due to the CO_2 thermodynamic properties, in particular, dry ice formation and pressure management.

3.2.3.1. Risks of dry ice formation

Pure CO_2 has a triple point at 5.18 bara and -56.6°C, and as shown in Figure 2. This means liquid CO_2 can only exist at temperatures and pressures above these values. Below the triple point, CO_2 can only exist in gas or solid form (dry ice). Dry ice formation hinders robust operation.

The risk of CO_2 freezing exists at various stages of an integrated terminal utilizing LNG cold recovery for cryogenic CO_2 liquefaction, as detailed in Table 9. The risk increases with significant pressure drops and low temperatures, particularly when pressure is already near to the triple point.

Table 9 – CO_2 freezing risk and mitigations at specific process stages in an integrated LNG receiving and CO_2 liquefaction terminal

Process stage	Hazards	Mitigation measures
Overall	Dry ice formation due to significant and rapid pressure drop leads to plugging, and equipment and material damage. The risk is higher in process stages dealing with higher compression levels and colder temperatures. The presence of impurities affects the physical properties of CO_2, such as the triple point, and phase behaviour compared to pure CO_2.	Maintaining sufficient operational margins (temperature/pressure) is crucial to prevent dry ice formation risks. Precise temperature and pressure control is essential to prevent temperatures from dropping below the CO_2 freezing point. Adopt reliable purification technology and monitoring CO_2 quality at the CO_2 receiving facilities.
Pipelines, valves	Solid CO_2 formation can cause blockages in pipelines, valves, and pressure relief valves (PRV).	Maintaining sufficient operational margins.
Liquefaction	CO_2 can freeze inside heat exchangers when temperatures drop below the triple point (-56.6°C at 5.18 bar), particularly during LNG cold recovery processes where temperatures are extremely low.	Precise temperature control. Prioritize indirect heat exchange for cold utilization to mitigate the risk of freezing.
Storage	Solid CO_2 formation due to malfunctioning temperature control or rapid pressure decrease.	Efficient and continuous monitoring systems are key to detecting and addressing temperature or pressure deviations promptly.

For liquefaction with cold utilization, direct heat exchangers are less expensive, but the risk of CO_2 freezing necessitates a cautious approach. CO_2 freezing during liquefaction remains one of the greatest uncertainties regarding LNG cold recovery for CO_2 liquefaction, making indirect heat exchange the recommended technology. Two existing CO_2 liquefaction facilities in Japan employ LNG as a refrigerant [10], utilizing distillation columns combined with intermediate fluid vaporizer (IFV) heat exchangers.

CO_2 freezing can lead to process disruptions such as blockages, equipment damage, and operational inefficiencies, potentially resulting in extended downtime and increased maintenance costs. Table 10 summarizes recommended strategies for mitigating CO_2 freezing risks.

Table 10 – CO_2 freezing risk mitigation strategies

Mitigation strategy	Description
Operational margins	Adopt sufficient temperature and pressure operational margins to prevent dry ice formation.
Temperature Monitoring	Ensure precise temperature control in all process blocks.
Heat Exchange Method	Prioritize indirect heat exchange to mitigate the risk of freezing.
Pressure Management & Monitoring	Implement efficient and continuous monitoring systems for temperature and pressure.
Impurities Management	Monitor CO_2 quality at the CO_2 receiving facilities. Adopt reliable purification technologies.
Supplier Instructions	Regularly review and verify supplier instructions and standards limits for CO_2 outlet temperatures.

Effective risk mitigation requires a combination of operational controls, precise temperature and pressure management, and strategic selection of heat exchange technologies. Continuous monitoring and pressure management are essential to ensuring safe and efficient CO_2 liquefaction and transportation.

3.2.3.2. Pressure management: Low and medium pressure

Efficient transport of captured CO_2 is key to the success of LCO_2 terminaling, and one effective solution is the shipping of CO_2 in liquid form (LCO_2) to offshore storage sites, such as depleted oil and gas reservoirs. Loading the CO_2 from the onshore temporary storage in the port to the CO_2 carrier can be performed using conventional articulated loading arms, developed for other cryogenic liquids such as LNG. The liquid is transferred through an insulated pipeline, specified for the chosen pressure and temperature, from the storage to the loading arm and ship, using pumps located near the storage. A second line returns boil off gas from the ship's tanks either to the onshore storage tanks or to the liquefaction plant.

Two pressure conditions are expected to be employed for LCO_2 transportation in the short and medium term, low and medium pressure, as summarized in Table 11. These pressure levels are designed based on LCO_2 carriers' technologies and to optimize the efficiency and safety of LCO_2 transportation.

Table 11 – CO_2 ship transport pressure conditions

Transportation pressure condition	Description
LP	Transportation around 7 barg. Expected to become more cost-effective and superior for handling larger volumes in a CCS chain.
MP	Transportation around 15 barg. Currently utilized in commercial CO_2 transport at small scale (food grade CO_2).

When filing the carrier with LCO_2 from the temporary storage, and to avoid over-pressurization, the same volume of gaseous CO_2 must be extracted and redirected to the liquefaction unit. As mentioned in section 3.1.3.1., the operating conditions in terms of pressure and temperature of the terminal temporary storage tanks should preferentially be the same as the ship's storage ones.

Configurations with different conditions can be imagined but several questions appear when combining low or medium pressure liquefaction with shipping at a different pressure. Figure 3 presents the different possible terminal pressure configurations.

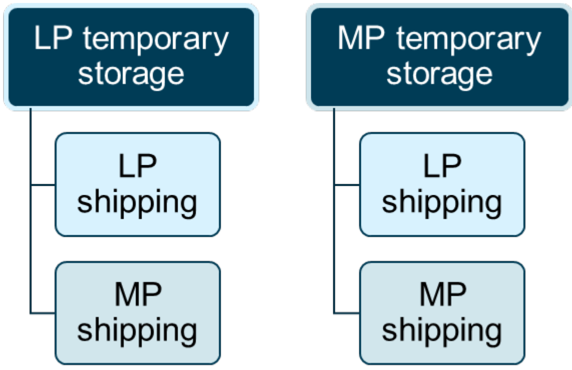


Figure 3 – Possible pressure combinations for LCO_2 transport

In the event of excess of boil-off gas during loading, storage, or from the LCO_2 carrier, it must be managed by the liquefaction unit. Currently, there is limited feedback on LCO_2 cargo handling but analogies with LNG can be made.

Table 12 outlines pressure management for loading LCO_2, considering different pressure conditions between temporary terminal storage and the ship storage.

Table 12 – Pressure management during LCO_2 loading operations

Loading condition	**Description**	**Risk**	**Mitigation measure**
LP to MP loading	LCO_2 is stored temporarily at lower pressure and lower temperature than the saturation temperature at medium pressure. LCO_2 is pumped up to the pressure of the carrier.	Pressure drop leading to increased freezing risk due to thermal gradients and CO_2 vapor condensation. Incompatibility between the design temperature of the ship's cargo tank at MP and the LCO_2 temperature at LP.	Manage pressure differential and flowrates using control systems. Warming up the LCO_2 (heater installed after LCO_2 booster pumps) to comply with MP ship cargo tank materials design temperature.
MP to LP loading	LCO_2 is stored temporarily at medium pressure and loaded at LP, leading to significant boil-off generation and flowrate.	Significant boil-off generation.	Manage pressure differential and flowrates using control systems. Use a de-superheating unit to reduce pressure and temperature with a Joule-Thomson valve.

3.3. Impacts on operation of the LNG receiving terminal

As a preamble, it should be recalled that when we address the issues of maritime interface and jetty design, many parameters are linked to the geography of the terminal site and its specific characteristics and are independent of the nature of the cargo. These local specificities already explain the diversity that can be observed between the different jetties of the LNG terminals.

However, the LNG industry benefits from its long history and the feedback accumulated from different sites and projects. Terminal operators and engineering companies can rely on numerous standards and abundant input data when designing new facilities. LCO_2 terminals are installations that do not exist to date and for which few standards are available. Although the design of maritime infrastructure can be inspired by the practices of the LNG industry, certain specific features, which we propose to develop below, will have to be taken into consideration.

3.3.1. LCO_2 Carrier Design

- Availability of data

To date, the fleet of LCO_2 carriers (LCO_2 C) dedicated to CCS comprises a few units currently under construction. Northern Lights JV is developing a fleet of four LCO_2 C vessels with a capacity of 7.5 km3, designed for MP mode of operation. Capital Gas is developing a fleet of two LCO_2 C vessels, each with a capacity of 22,000 m3, and operating in LP mode. At the same time, a number of companies are developing concepts of varying sizes. Regarding the concepts, the available data are incomplete and not entirely definitive. In the context of detailed engineering studies, the lack of precise data can present a challenge.

For instance, in the context of static or dynamic mooring studies, it is typically essential to have a mooring plan, a hull plan illustrating the flat body line and the anticipated characteristics of mooring lines in place. Furthermore, a 3D model of the hull is essential for dynamic mooring studies to simulate hydrodynamic behaviour.

At present, there are no LCO_2 C available in the database of specialized software for navigation studies. The creation of bespoke models will undoubtedly result in increased expenditure, time constraints, and the potential for intellectual property challenges, given the nascent state of this type of ship. It may be possible to select ships of equivalent size, but it should be noted that these ships will not necessarily have the same characteristics (draft, manoeuvrability, impact of sail propulsion systems, etc.). Some adjustments will therefore have to be made.

In the context of CO_2 projects, designers will therefore not always have access to the data they are accustomed to having for LNG projects. This is an acceptable approach for preliminary engineering phases (pre-FEED and FEED), but for the detailed engineering phase, it could potentially pose a challenge.

Figure 4 – Norther Pioneer - 7,5 k cbm CO_2 carrier (Credit: K Line)

- Vessel type / Manifold

LCO_2 MP vessels have volumes ranging from 5 km3 to 22 km3. These sizes are closer to those found for LNG bunkering vessels (LNGBV) rather than conventional LNGC, as presented in Table 11.

Table 13 – Ship typical characteristics

Type	**LCO_2 Carrier**				**LNGBV**	
Capacity (km3)	~8	~12	~20	~50 (LP)	5	18
LOA (m)	130	155	185	240	108	136
B (m)	21	25	27	39	18.4	25
Draft fully loaded (m)	8.3	8.5	9.5	12.5	4.7	6.8

However, design wise, LCO_2 vessels will be closer to LPG carrier than LNGBV. Indeed, given the characteristics of the products transported and the technology of the tanks, some CO_2 vessels will be built from start for a dual purpose, either for the transport of CO_2 or for the transport of LPG.

The 2018 SIGTTO/OCIMF standard "Recommendations for Liquefied Gas Carrier Manifolds" [11] distinguishes the case of LPG carriers from LNG carriers on several parameters including the height of the manifolds and manifold spacing.

Table 14 – Recommended height of LPG manifold above sea level (SIGTTO / OCIMF)

Category	From (m³)	To (m³)	Not greater than (m) *(at minimum operating draught)*	Not less than (m) *(at maximum operating draught)*
A1	-	6,000	10	2
A2	6,001	15,000	10	2
A3	15,001	25,000	12	4
A4	25,001	50,000	16	6
A5	50,001	70,000	16	6
A6	70,001	85,000	18	8
A7	85,001	-	18	8

Table 15 – LPG manifold size and horizontal distance (SIGTTO / OCIMF)

LPG Category	Manifold Diameter (DN)		Horizontal Distance (H)	
	Liquid (mm)	Vapour (mm)	Minimum (m)	Maximum (m)
A1	150	100	1.25	1.75
A2	200	150	1.25	1.75
A3	250	200	1.5	2.0
A4	300	200	2.0	2.5
A5 and A6	300/350	250	2.25	2.75
A7	400	300	2.25	2.75

Table 16 – Recommended height of LNG manifold above sea level (SIGTTO / OCIMF)

Category	From (m³)	To (m³)	Not greater than (m) *(at minimum operating draught)*	Not less than (m) *(at maximum operating draught)*
B1	-	6,000	12	4
B2	6,001	15,000	16	6
B3	15,001	25,000	18	8
B4	25,001	50,000	20	10
B5	50,001	70,000	22	12
B6	70,001	200,000	22	14
B7	200,000+	-	24	14

Table 17 – LNG manifold size and horizontal distance (SIGTTO / OCIMF)

LNG Category	Manifold Diameter (DN)		Horizontal Distance (H)	
	Liquid (mm)	Vapour (mm)	Minimum (m)	Maximum (m)
B1	150	150	1.5	2.0
B2	200	200	1.5	2.0
B3	250	250	2.0	2.5
B4	300	300	2.5	3.0
B5	300	300	2.5	3.0
B6	400	400	3.0	3.5
B7	400/500	400/500	3.5	4.0

As indicated in the tables above, a typical LPG carrier and an LNGBV of equivalent size have manifolds above the water line with heights that differ by 4 m to 6 m. Additionally, the manifolds on an LPG carrier are smaller and closer together than those on an LNG carrier. Given that the LCO_2 C design will likely be based on LPG carrier standards rather than LNG, these differences may present challenges in certain open port sites initially used for LNG traffic and subject to significant tidal ranges.

For vessels of equivalent size, LCO_2 arms will require a longer reach than typical LNG arms to accommodate lower heights at low tide for loaded ships. Furthermore, narrower manifolds will increase the likelihood of a clash between the arms.

It is essential that CO_2 terminal project developers consider these aspects when defining their requirements. For example, LCO_2 carriers of all potential sizes should be considered as reference ships in a long-term vision, given that it will take some time for the fleet to develop, which could result in difficulties and additional costs. It would be beneficial to ascertain which party (terminal or ship operator) would be best placed to optimize its design to suit the needs of the other party.

- Draft

It should be noted that CO_2 is noticeably heavier than LNG. For an equivalent volume, LCO_2 ships will require a larger draft than LNG carriers. For LCO_2 MP vessels up to 22k in size, the drafts will be equivalent to those of a conventional 160k LNG carrier. LCO_2 LP vessels up to 50k or 70k in size will have potentially drafts that are equivalent or even superior to those of a Qmax. While these large vessels are still in the conceptual stage, their arrival at docks typically reserved for LNG carriers or on converted LNG jetties could necessitate additional dredging and potentially structural modifications to accommodate their size.

- Shore Power

LCO_2 ships intended for CCS will be new and therefore will be equipped with devices allowing a shore power supply. While these devices are already in use in certain sectors, such as cruise ships and container ships, their application in the context of liquid bulk remains relatively limited.

Project leaders may encounter challenges in addressing this need. Indeed, there is currently no standard system in place to guarantee compatibility between all vessels. The location of this connection may also vary depending on the specific vessel in question. The location of the connection can be either in the manifold area or at the electrical room at the rear of the vessel (or at the front, depending on the vessel).

If the connection is located in the manifold area, it may be fore or aft of the CO_2 manifolds, given the lack of a standard addressing this matter. The SIGTTO/OCIMF standard related to the organization of manifolds does not currently address electrical connections.

In the case of a pier-type jetty with ample space, this issue can be addressed using mobile systems that can adapt their positioning based on the vessel in question. In the context of a sea island type jetty, it is essential for project developers to discuss these aspects as far in advance as possible with ship designers if the latter have already been identified. Otherwise, assumptions will have to be made with a risk of future compatibility with ships. It should also be noted that emergency disconnection systems for the power supply are not yet common at this stage.

3.3.2 Dual service jetty LCO_2 & LNG

It is anticipated that the announced capacities of LCO_2 terminals will remain limited in the medium term.

To maximize the utilization rate of their jetty and improve the profitability of their projects, project developers may wish to consider multi-traffic jetties, in particular CO_2 and small-scale LNG traffic for loading LNGBV or the quayside bunkering of LCO_2 vessels, a large proportion of which will be LNG-powered. This dual activity on a single site does, however, present certain challenges, particularly in terms of development and impacts on CO_2 installations.

- Layout

It is assumed that the LNG and LCO_2 loading stations are arranged side by side within the same jetty to share facilities and limit investments. This jetty must be able to accommodate LNGBVs with an LOA between 100 and 140 m and LCO_2 Cs between 130 and 200 m (case for MP ship size). Therefore, the maximum platform width should be 40 m (0.4 * 100 m) to comply with actual mooring standards (MEG4). However, this value appears insufficient to accommodate six unloading arms (three CO_2 and three LNG) as well as a gangway. This would necessitate the replacement of the LNG arms with either flexible hoses or a single piggyback arm, which could potentially lead to operational complexities and performance issues.

Furthermore, in the context of bunkering at the quayside of LCO_2 ships, the rationale behind this operation is the potential for it to be carried out without the need for unmooring and replacement of the vessel. Therefore, a flexible or piggyback arm solution would be the optimal choice.

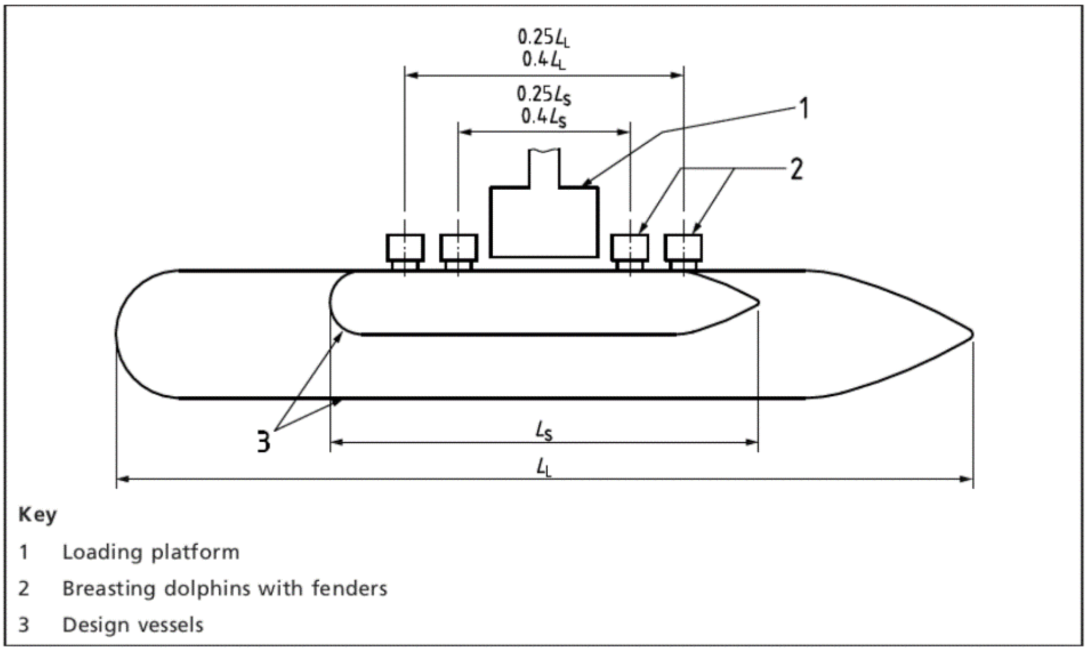


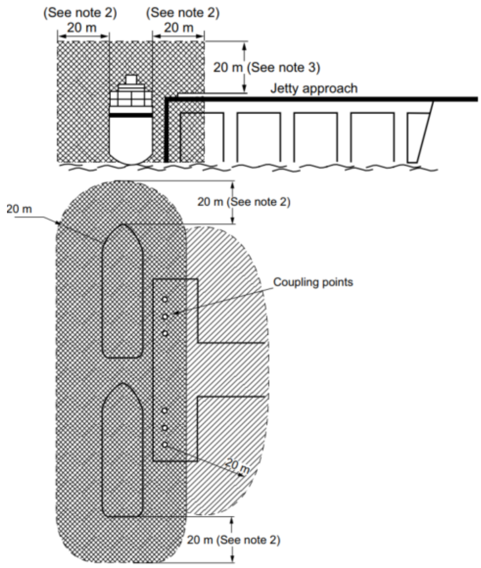
Figure 5 – Fender Layout - BS 6349 Marine Structures

- LNG Risks

Having a dual-service jetty will have consequences for CO_2 installations in view of the risks brought by LNG.

- Hazardous area

A first impact will be the implementation of the ATEX zoning. Indeed, the application of the EI15 standard specifies that in the context of ship loading, the LNGBV constitutes its own ATEX Zone 1 up to a distance of 20 m around its hull as shown in Figure 6. This distance will also encompass CO_2 equipment, which must be included in the agreement and will incur additional costs.



Notes:

1. The Zone 1 area is additional to any hazardous area assessed in consequence of all other equipment on the jetty.
2. Distance may be reduced to 15 m for vessels with loading or unloading rates of 10 m^3/min or less.
3. The hazardous area should extend 20 m above the coupling points. This may be reduced to 15 m for loading rates of 10 m^3/min or less.
4. For category A fluids, reference should be made to the approach in Chapter 3.
5. These distances may be conservative. However, they cover a great variety and size of ships which may be berthed for loading. If the size of the vents and loading rates are well-defined, 3.4. may be used to determine more specific hazard radii.

Figure D20: Jetties – loading facilities only

Figure 6 – LNG Loading facilities hazardous area (Ref EI15)

- Fire water requirements

Another consequence of this is the necessity for firewater. Given that LCO_2 is not flammable, a CO_2 jetty does not require a specific fire water supply. At present, no standard defines these requirements. Should this jetty be designed for LNG services as well, the standard ISO 28460 will apply. Therefore, it is essential to consider the installation of fire monitors, deluge systems, and foam generators in the LNG impounding basin, for instance. The incorporation of these elements into a jetty primarily engaged in CO_2 activities will undoubtedly result in a notable increase in costs.

- Shore Fuel bunkering of LCO_2 vessels

It is anticipated that the majority of LCO_2 carriers will be LNG-powered initially. For LNG terminal owners, developing a CO_2 terminal activity could represent an opportunity to proceed to their bunkering from the quay, with the potential for cost savings for the final end-user. It should be noted, however, that this activity (direct fuel bunkering at the quay of an LNG-powered cargo) is not a typical service offered by LNG terminal operators at present.

This activity presents a number of challenges:

- Custody transfer: In the case of loading a LNG vessel, the custody transfer is conducted via the ship's system. In a ship-to-ship refuelling operation, the bunkering vessel utilizes its own Custody Transfer Measurement System (CTMS) system to determine the quantity transferred. It should be noted that a CTMS based on shore tank volume is not available at an onshore LNG terminal. It would therefore be advisable to consider the installation of a dedicated fiscal metering skid.
- Ship-shore link: The objective is to optimize the time schedule for CO_2 loading and LNG fuel bunkering in SIMOPS. However, a proper risk assessment must be conducted prior to allowing such operations.

Additionally, a number of technical aspects must be studied, including the ship-shore link, which could present a challenge given the need to interact with both the LNG terminal and the LCO_2 terminal process simultaneously.

4. Opportunities and projects mapping

As previously explained, rising interest and the ongoing development of CCS projects are driving the need for infrastructure to condition and transport CO_2 to storage sites. Transporting CO_2 over long distances often requires liquefaction, making LCO_2 export terminals essential for liquefying and loading CO_2 into carriers.

CO_2 liquefaction requires a significant amount of energy, adding to operational expenses of projects. Unlike LNG, CO_2 is liquefied at higher temperature, allowing it to benefit from colder sources of waste heat. This is particularly advantageous when CO_2 liquefaction is performed near an LNG regasification terminal, where the cold energy from LNG is often not exploited. Utilizing this waste cold energy to liquefy CO_2 presents a great opportunity to reduce energy consumption, OPEX and emissions.

Beyond liquefaction, CO_2 can benefit from LNG in other segments. On the maritime side, LCO_2 infrastructure can draw inspiration from the LNG industry. Although LCO_2 vessels differ in design and size from LNG carriers, jetties can be updated to accommodate multi-fluid activities, thereby enhancing projects' profitability.

Additionally, it is likely that LCO_2 carriers will be powered by LNG. If the LNG terminal does not already offer LNG as fuel bunkering, this presents a new service opportunity, further improving project profitability.

Interest in CO_2 terminals is rising with CCS development. The list below maps the LCO_2 terminals projects, providing a concise description of each.

Disclaimer: the LCO_2 projects list proposed is non-exhaustive and may evolve.

1. Dunkerque CO_2 terminal [12]: As part of D'Artagnan project [13], an LCO_2 export terminal is planned close to Dunkerque LNG import terminal, as part of a partnership between Dunkerque LNG and Air Liquide. The CO_2 terminal, presented in Figure 7, is also part of "Cap Décarbonation", a decarbonizing industry initiative, carried out in collaboration with Air Liquide, France Industrie, Dunkerque LNG, EQIOM, Lhoist and RTE.

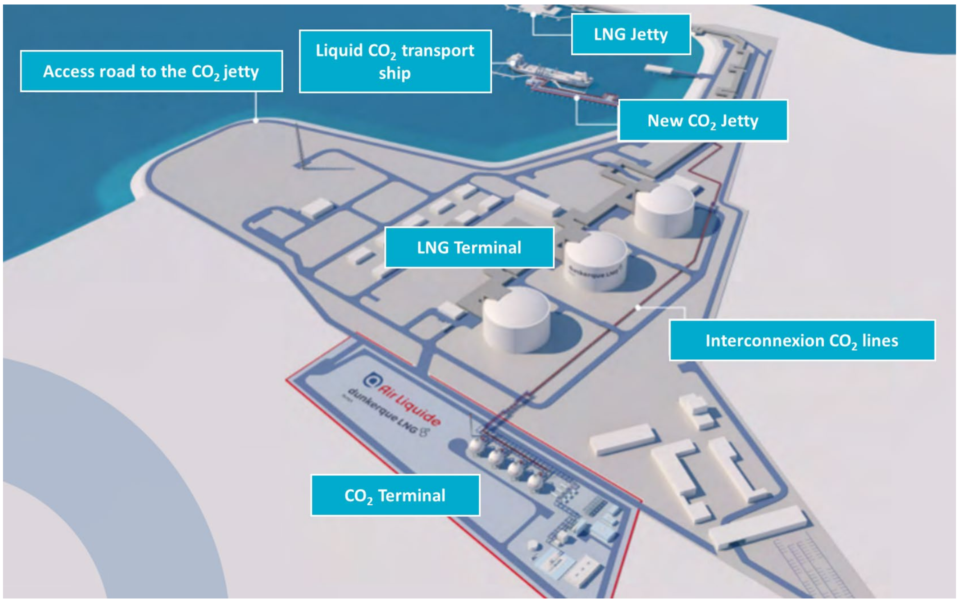


Figure 7 – Dunkerque terminal [14]

The CO_2 inlet is in dense phase. In the first phase of the project, nominally by 2028, the objective is to conceive a CO_2 terminal with a capacity of 1.5 million tonnes per year. After the first phase, the liquefaction process might include LNG cold utilization from the LNG terminal.

2. CO_2 Next: project aims to build a LCO_2 receiving terminal at the Maasvlakte in the port of Rotterdam. Customers not connected to a CO_2 pipeline would benefit from this infrastructure and ship their LCO_2. The technical feasibility and development of such CCS chain is jointly explored with the Aramis CCS project, to which the terminal will be connected. The terminal's initial capacity is around 5.4 million per year [15]. The Final Investment Decision (FID) is planned for 2025 and operations in 2028.

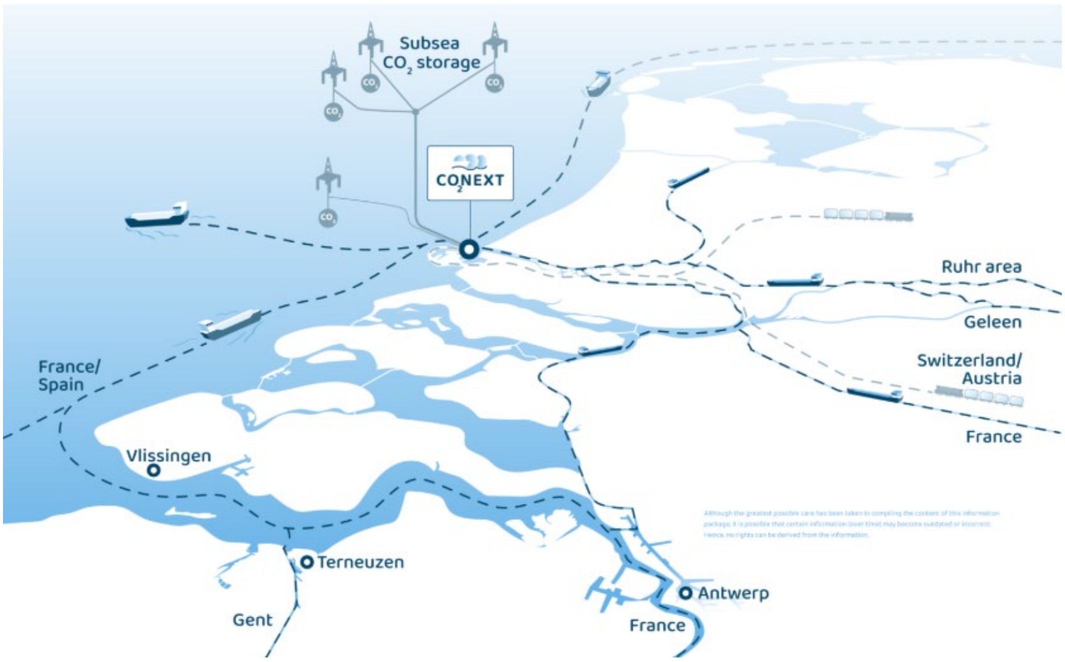


Figure 8 – CO_2 Next project [15]

3. Grand Ouest CO_2 ($GOCO_2$): the project aims to capture, transport, liquefy and export CO_2 from industrial sites in Pays de la Loire and Bretagne regions in France to sequestration sites. The estimated capacity is 2.3 million tonnes per year by 2031 [16]. Heidelberg Materials, Lafarge, Lhoist and NaTran are partners of Elengy for the development of $GOCO_2$.

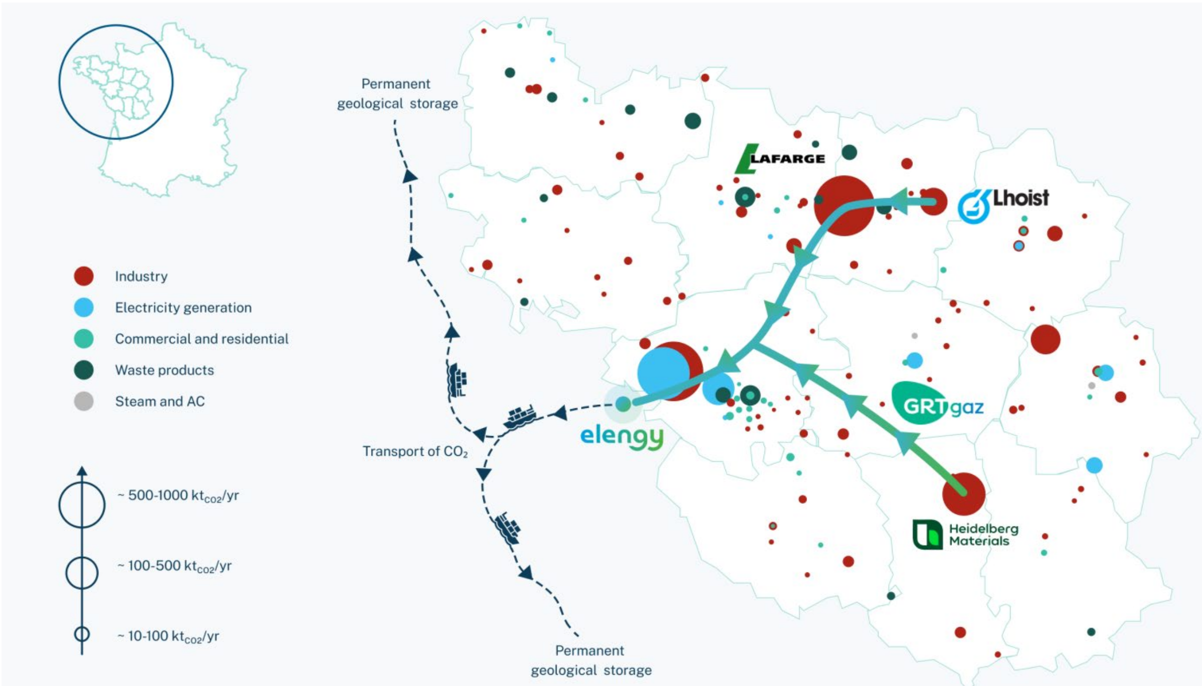


Figure 9 – $GOCO_2$ project [16]

4. RhoneCO_2: is a CO_2 transport network and a liquefaction and export terminal project for the Rhône Valley aiming to decarbonize the industrial sector in the region, promoted by “Société du Pipeline Sud-Européen” (SPSE) and Elengy.

5. CO_2 nnectNow: Wintershall Dea and HES Wilhelmshaven Tank Terminal aim to develop a CO_2 export terminal at Wilhelmshaven Green Energy Hub in Germany. The CO_2 terminal would receive CO_2 from emitter sites via pipeline and rail (and potentially shipping in the future). CO_2 will be stored temporarily and transported permanently in the North Sea. Overall, it would be possible to handle up to 10 million tpa of CO_2. The terminal operations could start in 2029.

6. JFY2021 - CO_2 Ship Transportation: A consortium comprising Japan CCS, the Engineering Advancement Association of Japan, ITOCHU Corporation, Nippon Gas Line, and NIPPON STEEL was formed in 2021 by the New Energy and Industrial Technology Development Organization (NEDO) to conduct this project. The project aims to develop and demonstrate long-distance CO_2 ship transportation from emission sources to utilization or storage points, as illustrated in Figure 10, at a scale of 1 million tonnes per year.

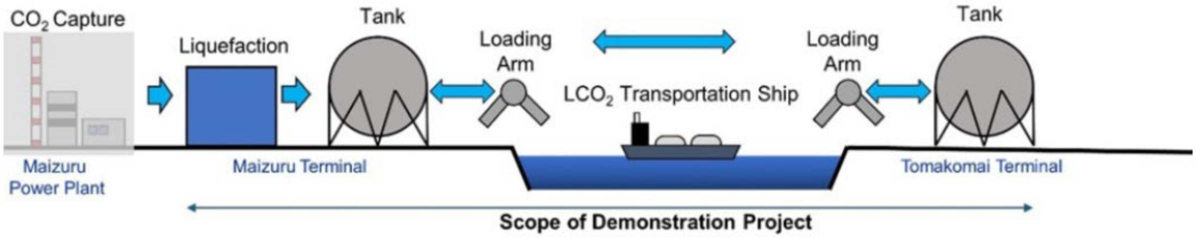


Figure 10 – Japan's CO_2 R&D ship transportation project [17]

CO_2 will be liquefied in the Maizuru Power Plant's terminal and transported back-and-forth between the Tomakomai terminal and Maizuru terminal.

5. Conclusions & Recommendations

LNG receiving terminals produce natural gas by vaporizing LNG, generating cold energy that can be harnessed in the CO_2 liquefaction process at LCO_2 export terminals. This synergy between LCO_2 and LNG presents a remarkable opportunity for substantial OPEX and CO_2 emissions reductions in LCO_2 operations, offering significant environmental and economic benefits.

While associated operations are complex, and safety impacts must be considered and mitigated, the potential advantages are substantial. The main challenges identified are:

- Safety hazards: LNG vapor is flammable and, although CO_2 is not, CO_2 installations must comply with ATEX classification zone safety requirements when sharing a location with LNG. The proximity of both substances could complicate emergency response operations. Recovering cold energy from LNG in the CO_2 liquefaction process requires an intermediate fluid, and the additional risks of the three fluids must be analysed and mitigated.
- Thermodynamic properties: LCO_2 requires specific handling and storage conditions due to its thermodynamic properties. Any deviation from these conditions could lead to operational issues, such as blockages from dry ice formation. Like LNG, LCO_2 generates boil-off gas during storage, transfer, and transportation, which requires proper management. Additionally, impurities in CO_2 can lead to acid formation and corrosion (e.g., NOx, H2S).
- Process flexibility and operation: Integrating both terminals introduces additional complexity. Additional training and adapted process design are necessary, particularly to manage LNG and CO_2 availability and terminal flexibility. A cold back-up cycle for CO_2 liquefaction and a back-up heating method for LNG vaporization are essential.
- Sharing of loading facilities: Carrier designs differ between LNG and LCO_2, with the latter requiring larger drafts and different manifolds sizes.
- Regulatory compliance: Ensuring both terminals meet their respective safety and environmental regulations. Each terminal may require a specific approach.

The LNG industry has long benefited from extensive operational experience and feedback from multiple sites and projects, providing accessible industry standards and valuable design data. In contrast, LCO_2 terminals are a new development. Despite the lack of operational feedback from LCO_2 terminals, the LNG industry is well-positioned to help develop this new activity. Decades of LNG industry expertise and the availability of free cold energy offer significant advantages for CO_2 terminal development. Moving forward, the development and operation of announced, and upcoming projects will play a key role in derisking proposed integration schemes, enhancing expertise in LCO_2 terminal operations, and maximizing the potential synergies between these industries.

References

[1] Health and Safety Executive UK, "General hazards of Carbon Dioxide." Accessed: Jan. 27, 2025. [Online].
Available: https://www.hse.gov.uk/carboncapture/carbondioxide.htm

[2] Asia Industrial Gases Association (AIGA), "AIGA 074 - Safe handling of CO2 containers that have lost pressure." 2009. [Online].
Available:https://www.asiaiga.org/uploaded_docs/AIGA%20074_11%20Safe%20handling%20of%20CO2%20containers%20that%20have%20lost%20pressure_Reformated%20Jan%2012.pdf

[3] BCGA, "CP26 Bulk liquid carbon dioxide storage at users' premises. Revision 3: 2012," BCGA. Accessed: Jan. 27, 2025. [Online].
Available: https://bcga.co.uk/publications/cp26-bulk-liquid-carbon-dioxide-storage-at-users-premises-revision-3-2012/

[4] IPCC, "Special Report on Carbon dioxide Capture and Storage." [Online].
Available: https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter4-1.pdf

[5] Penspen, "Assessing Safety Risks for CO2 Pipelines," Penspen. Accessed: Jan. 27, 2025. [Online].
Available: https://www.penspen.com/insights/assessing-safety-risks-for-co2-pipelines/

[6] Wikipedia, "Mazuku," *Wikipedia*. 2025. Accessed: Jan. 27, 2025. [Online].
Available: https://en.wikipedia.org/wiki/Mazuku

[7] EIGA, "Doc 66/22 Refrigerated Carbon Dioxide Storage at Users' Premises." [Online].
Available: https://www.eiga.eu/uploads/documents/DOC066.pdf

[8] Health and Safety Executive UK, "Assessment of the major hazard potential of carbon dioxide", [Online].
Available: http://www.hse.gov.uk/carboncapture/assets/docs/major-hazard-potential-carbon-dioxide.pdf

[9] Wood, "Industry Guidelines for Setting the CO2 Specification in CCUS Chains," Wood. Accessed: Feb. 28, 2025. [Online].
Available: https://www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains

[10] C. Weidon, H. Zhifeng, and C. Kian Jon, "Thermal Energy Waste Recovery Technologies and Systems.," 2023.

[11] SIGTTO - The Society of International Gas Tanker and Terminal Operators, "Recommendations for Liquefied Gas Carrier Manifolds." Accessed: Dec. 09, 2024. [Online].
Available: https://www.sigtto.org/publications/recommendations-for-liquefied-gas-carrier-manifolds/

[12] "Terminal CO_2 de Dunkerque." Accessed: Jan. 22, 2025. [Online].
Available: https://www.fluxys.com/fr/projects/dunkirk-co2-export-terminal

[13] "Le projet D'Artagnan." Accessed: Jan. 22, 2025. [Online].
Available: https://cap-decarbonation.fr/fr/le-projet-d-artagnan-dunkerque

[14] Air Liquide, Dunkerque LNG, EQUIOM, Lhoist, and RTE, “Cap Décarbonation - Une démarche pionnière vers la neutralité carbone du ciment et de la chaux,” May 2024. [Online]. Available: https://cap-decarbonation.fr/fr/les-documents

[15] “CO2next website,” CO2next Liquified CO2 terminal. Accessed: Jan. 22, 2025. [Online]. Available: https://co2next.nl/about/

[16] “Elengy | GOCO2, Grand-Ouest CO2.” Accessed: Jan. 22, 2025. [Online]. Available: https://www.elengy.com/en/media/our-projects-making/goco2-grand-ouest-co2

[17] “Research, Development and Demonstration Projects on CO2 ship Transportation | PROJECTS | Japan CCS Co., Ltd.” Accessed: Apr. 14, 2025. [Online].

Available: https://www.japanccs.com/en/business/co2/index.php