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Advancing Liquefied CO_2 Shipping: Technical Considerations for Ship Cargo System Design

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ABSTRACT

The maritime transport of liquefied carbon dioxide (LCO_2) is emerging as a critical enabler for large-scale carbon capture and storage (CCS) deployment, addressing the logistical challenge of connecting dispersed emission sources with remote storage sites. This paper provides an analysis of LCO_2 ship cargo system design, focusing on the thermodynamic properties of CO_2 and their implications for shipboard cargo containment, safety, and operational efficiency. This paper reviews the current fleet of LCO_2 carriers and highlights the technological advancements required to meet the demands of future CCS projects, including larger vessel capacities and optimized pressure-temperature regimes. Key design considerations, such as avoiding solid CO_2 formation near the triple point and managing impurities, are discussed alongside regulatory frameworks. Furthermore, this paper explores the feasibility of multifunctional cargo systems for transporting other liquefied gases, such as ethane, ammonia, and liquefied petroleum gas, and the potential for direct ocean injection, while acknowledging the associated environmental and regulatory challenges. The findings underscore the need for innovative engineering solutions to ensure the safe, efficient, and scalable implementation of LCO_2 shipping within the global carbon management infrastructure.

Keywords: carbon capture and storage, liquefied carbon dioxide, maritime transport, shipping, ship, tank, design.

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1 INTRODUCTION

Global anthropogenic carbon dioxide (CO_2) emissions remain a central driver of climate change, accounting for approximately 76% of total greenhouse gas (GHG) emissions (Center for Climate and Energy Solutions [C2ES], 2025). In 2024, global CO_2 emissions from using fossil fuels reached a record high of 37.4 billion tonnes, up 0.8% from 2023 (Global Carbon Budget, 2024). Limiting global temperature rise to below 1.5 °C, as outlined in the Paris Agreement, requires rapid and deep CO_2 emission reductions across all sectors. In response, governments and industries worldwide are implementing a range of mitigation strategies, including active measures such as the increased use of low-carbon and renewable energy, and passive approaches like CO_2 removal technologies. Among these, carbon capture and storage (CCS), including carbon capture, utilization, and storage (CCUS)—hereafter collectively referred to as CCS—has emerged as a critical technology for decarbonizing hard-to-abate sectors such as cement, steel, and chemicals (Griffiths & Uratani, 2025), as well as enabling the production of blue fuels—such as blue hydrogen and ammonia—derived from fossil sources like natural gas or coal, with CCS technologies applied to significantly reduce GHG emissions during production (Al-Yafei et al., 2025; Massarweh et al., 2023). According to the International Energy Agency (IEA), achieving global net-zero targets under the Sustainable Development Scenario in 2070 will require capturing 3–4 billion tonnes of CO_2 annually by 2040 and 5–6 billion tonnes by 2050 (IEA, 2020), up from the 51 million tonnes captured globally in 2024 (Global CCS Institute, 2024). As of the end of 2024, there are 50 CCS facilities in operation worldwide, 44 under construction, and 534 in development, representing a total capacity of approximately 500 million tonnes of CO_2 per year (Global CCS Institute, 2024).

A major logistical challenge in the deployment of CCS is the geographical mismatch between CO_2 capture sites—typically situated near industrial hubs—and suitable geological storage formations, such as depleted oil and gas reservoirs and deep saline aquifers, many of which are located offshore or in remote inland regions (Neele et al., 2017). For instance, as illustrated in Figure 1 (IOGP, 2025), in Europe, the majority of CO_2 storage projects—at various stages of development—are concentrated in the North Sea region, whereas the CO_2 capture projects are more widely distributed across different countries. This spatial separation underscores the growing need for flexible and scalable CO_2 sea transport solutions to effectively connect emission sources with storage sites.

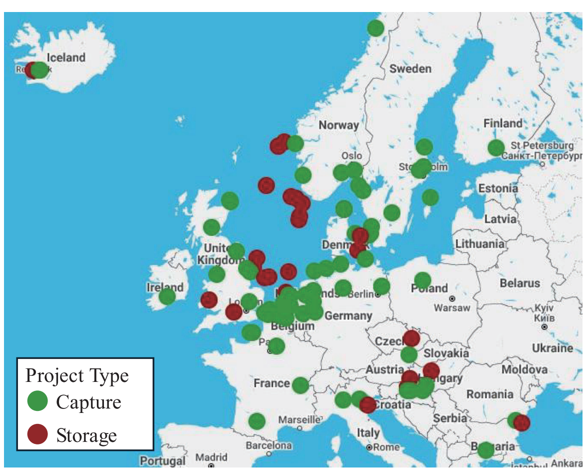

Figure 1. Carbon capture, and storage projects in Europe. (Data source: IOGP, 2025)

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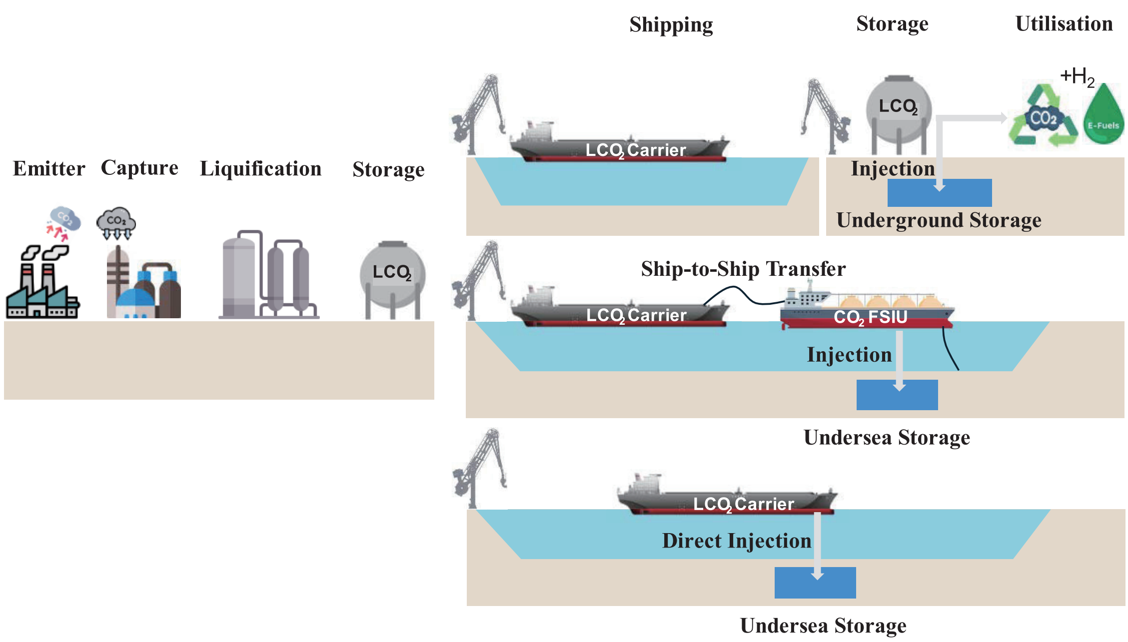
While pipelines have traditionally dominated CO_2 transport infrastructure (Lu et al., 2020; Onyebuchi et al., 2018), their capital intensity, permitting complexity, and inflexibility over long distances or across borders limit their applicability in many regions. In this context, the maritime transport of liquefied CO_2 (LCO_2) offers a promising and increasingly viable alternative (Al Baroudi et al., 2021). Shipping enables cross-border transport of CO_2 at scale, offering adaptability in coastal regions with dispersed sources and sinks. On the other hand, transporting CO_2 in liquid form rather than as a gas offers significant advantages in density and efficiency. At 20 bar and –30 °C, LCO_2 has a density of 1,078 kg/m³—approximately 544 times that of gaseous CO_2 at standard temperature and pressure (1.98 kg/m³)—enabling more compact and cost-effective storage and transport (Anwar & Carroll, 2016; Wischnewski, 2007). Unlike gaseous CO_2, which requires high-pressure infrastructure, LCO_2 can be transported at lower pressures—typically less than 20 bar—in insulated, refrigerated tanks, reducing infrastructure costs and making it the preferred option for large-scale CCS deployment.

The CCS supply chain using LCO_2 as the transport medium involves multiple interconnected stages, as illustrated in Figure 2. It begins at CO_2 emission sources, where CO_2 is captured. The captured CO_2 is then purified and liquefied. The LCO_2 is then transferred to onshore terminal storage facilities before being transported by specialized LCO_2 carriers to either onshore receiving terminals or offshore facilities, such as floating storage and injection units (FSIUs) (Det Norske Veritas [DNV], 2025). At onshore terminals, the CO_2 is either injected into geological formations for permanent storage or utilized as a feedstock for producing green fuels such as synthetic methane or methanol. At offshore FSIUs, the CO_2 is injected into undersea storage formations. Alternatively, the CO_2 may be directly injected from the LCO_2 carrier if equipped with onboard injection systems. This integrated supply chain facilitates large-scale emissions reduction while supporting the development of a circular carbon economy.



CO_2: Carbon dioxide; LCO_2: Liquefied carbon dioxide; H_2: Hydrogen; FSIU: Floating storage and injection unit.

Figure 2. Supply chain of carbon capture, and storage.

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Recent mapping of CCS projects by the Global CCS Institute and the International Association of Oil & Gas Producers (IOGP) highlights a rising number of planned facilities in Europe and the Asia-Pacific region that envision maritime LCO_2 transport as a core logistical component. Projects such as Norway's Northern Lights, the Netherlands' Porthos, and Australia's Bayu-Undan illustrate this emerging trend (Global CCS Institute, n.d.; IOGP, n.d.). In parallel, shipowners and maritime stakeholders are showing growing interest in LCO_2 shipping. Multiple feasibility studies and vessel designs have been conducted (Danish Technological Institute & Maersk Broker Advisory Services, 2022; Element Energy, 2018; Larsen et al., 2022; Tanaka et al., 2022), with ship types ranging from small-scale feeders to large transoceanic LCO_2 carriers.

With the accelerating deployment of CCS projects globally and the pivotal role of maritime transport in facilitating cross-regional CO_2 transfer, the development of dedicated LCO_2 carriers has become an urgent and strategically significant area of research. The design of these carriers entails specialized LCO_2 cargo systems and presents distinct engineering, safety, and operational challenges arising from the unique thermophysical properties of CO_2. This paper presents a comprehensive analysis of key design considerations for LCO_2 carriers and proposes cargo system design recommendations to support the safe, efficient, and scalable implementation of maritime CO_2 transport within the emerging carbon management supply chain.

2 RESEARCH METHODS

The research methodology is structured in three phases: (1) a review of current LCO_2 carrier technologies and operational practices; (2) a functional analysis of LCO_2 cargo systems based on the thermophysical properties of CO_2, with emphasis on key design considerations; and (3) an exploration of multifunctional cargo system designs aimed at enhancing economic viability, including configurations for transporting multiple gases and enabling direct ocean injection.

In the first phase, peer-reviewed academic publications, industry white papers, and shipowner reports were reviewed to identify the current state of development in LCO_2 carrier design. Particular attention was given to early prototype vessels, ongoing projects, and commercial designs under consideration or development. Technical characteristics such as cargo containment systems, pressure and temperature conditions, and ship capacity were extracted and synthesized to build a foundational understanding of the prevailing design trends and challenges.

In the second phase, the thermophysical properties of CO_2 were examined to derive the performance requirements of onboard cargo systems. Key thermodynamic parameters, including triple point, critical point, and phase stability, were considered to assess their influence on storage system design. Based on these properties, the study evaluates the functional requirements of cargo systems and supporting safety systems. This analysis draws on principles of chemical engineering, mechanical engineering, process systems design, and marine cargo operations.

The third phase explores innovative design strategies to enhance the economic feasibility of LCO_2 carriers by incorporating multifunctional capabilities. This includes the potential integration of multi-gas transport systems covering ammonia and liquefied petroleum gas (LPG) and the addition of direct ocean injection systems for offshore CCS operations.

Together, these phases provide a comprehensive methodology for evaluating the current state, functional design, and future development pathways of LCO_2 shipping systems within the CCS supply chain.

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3 RESULTS AND DISCUSSION

3.1 Development of LCO_2 Ships

LCO_2 shipping has been practiced for over 30 years, primarily supporting the food and beverage industry's demand for CO_2. The first purpose-built CO_2 ship, designed specifically for this application, was launched in Norway in 1988 (Element Energy, 2018). Since then, a small fleet of dedicated LCO_2 carriers has been developed, operating mainly in Europe. Due to the relatively limited scale of annual CO_2 trade flows to date, existing LCO_2 ships are significantly smaller than the vessel sizes anticipated for future large-scale CCS projects. Most existing LCO_2 carriers typically have cargo capacities ranging from a few hundred cubic meters up to around two thousand cubic meters, compared to the future large vessels envisaged for CCS-focused designs. Table 1 lists the existing eight LCO_2 carriers in the world (Clarksons Research, 2025).

Table 1. Existing LCO_2 carriers.

Name	Owner	Built	Flag	DWT	Capacity (m^3)	Tank pressure (bar g, gauge pressures)	Tank temperature (℃)
Helle	Nippon Gases Europe	1999	Norway	1,786	1,265	18	–40
Gerda	Nippon Gases Europe	2004	Norway	3,480	1,800	19	–30
Embla	Nippon Gases Europe	2005	Norway	3,481	1,800	19	–30
Froya	Nippon Gases Europe	2005	Norway	3,486	1,800	19	–30
Excool	Sanyu Kisen	2023	Japan	1,261	1,462	19.3	–50
De Jin 26	Zhoushan Dejin	2024	China	494	504	25	–30
Northern Pioneer	Northern Lights	2024	Norway	10,189	7,500	19	–35
Northern Pathfinder	Northern Lights	2024	Norway	10,189	7,500	19	–35

Data source: Clarksons Research, World Fleet Register, until 1st May 2025. (Clarksons Research, 2025)

Existing vessels are generally designed for medium-pressure transport conditions, operating at pressures between 18 and 25 bar g (gauge pressures) and at temperatures from –50 °C to –30 °C. This specification provides a balance between manageable vessel construction requirements and operational safety, while matching the needs of current industrial CO_2 users.

To support the scale-up required for CCS applications, more large vessels have been ordered, as listed in Table 2. The maximum LCO_2 carriers on the orderbook have reached 22,000 m^3, which adopt low-pressure cargo tanks. Currently, alternative pressure-temperature regimes are being investigated and adopted. Low-pressure, low-temperature transport solutions (approximately 7–10 bar g and –50 °C) are of particular interest (DNV, 2022), as they can reduce the shipping cost per unit volume of CO_2 by lowering tank pressure requirements and enabling larger tank capacities. However, from a supply chain perspective, the lower temperatures increase the energy demand and cost associated with CO_2 liquefaction and conditioning prior to loading. Conversely, high-pressure transport solutions (approximately 40–50 bar and temperatures above 0 °C) are also under study (The Maritime Executive, 2024). These systems may allow integration with emerging high-pressure CO_2 pipelines and injection systems, potentially simplifying terminal operations and offshore storage processes, albeit at the expense of higher tank material strength requirements and reduced volumetric efficiency.

Table 2. LCO_2 carriers on order.

Name	Owner	Built	Company country	DWT	Capacity (m^3)	Tank pressure (bar g, gauge pressures)	Tank temperature (℃)
TBN	Northern Lights	2025	Norway	10,170	7,500	19	–35
Active	Capital Clean ECC	2025	Greece	27,926	22,000	(Low-pressure)	–55
Greensand Future	Wagenborg Shipping	2025	Netherlands	14,300	5,272	Unknown	Unknown
Alkimos	Capital Clean ECC	2026	Greece	27,926	22,000	(Low-pressure)	–55
Athenian	Capital Clean ECC	2026	Greece	27,926	22,000	(Low-pressure)	–55
Amadeus	Capital Clean ECC	2026	Greece	27,926	22,000	(Low-pressure)	–55
TBN	Schulte Group	2026	Germany	10,170	7,500	Unknown	Unknown

Data source: Clarksons Research, World Fleet Register, until 1st May 2025 (Clarksons Research, 2025).

Overall, while the existing fleet of LCO_2 carriers provides a valuable foundation of operational experience, the scale, operating conditions, and technological requirements for CCS-related CO_2 shipping are expected to differ substantially, requiring new vessel designs and supply chain adaptations.

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3.2 CO_2 Phase Diagram and Implications for LCO_2 Ship Cargo System Design

3.2.1 CO_2 phase diagram

The CO_2 phase diagram can be systematically understood by considering four major regions, two characteristic points, and three important phase boundaries, as shown in Figure 3.

The four regions define the stable phases of CO_2 under different pressure and temperature conditions:

- Solid CO_2 (dry ice) exists at low temperatures.
- Liquid CO_2 and gaseous CO_2 occupy an intermediate range of temperature and pressure, and are divided by the saturation line.
- Supercritical fluid appears when both pressure and temperature exceed the critical point; in this state, CO_2 exhibits properties of both a gas and a liquid without a distinct phase boundary.

Two key points characterize major transitions on the diagram:

- The triple point (5.18 bar and –56.4 °C) is the unique condition where solid, liquid, and gas phases coexist in equilibrium.
- The critical point (73.8 bar and 31.1 °C) marks the end of the liquid-gas boundary, beyond which distinct liquid and gas phases no longer exist, and CO_2 becomes super-critical.

Three phase boundaries separate the different regions:

- The saturation line (or vapor-liquid equilibrium line) delineates the boundary between the liquid and gaseous phases below the critical point. Along this line, CO_2 can transition between liquid and gas through evaporation or condensation.
- The sublimation line defines the boundary between the solid and gas phases at pressures below the triple point. Crossing this line results in direct transitions between solid and gas without passing through the liquid phase.
- The melting line separates the solid and liquid phases at pressures above the triple point. Along this line, CO_2 transitions between solid and liquid through melting or freezing.

Understanding the CO_2 phase diagram is critical for designing LCO_2 cargo systems for ships.

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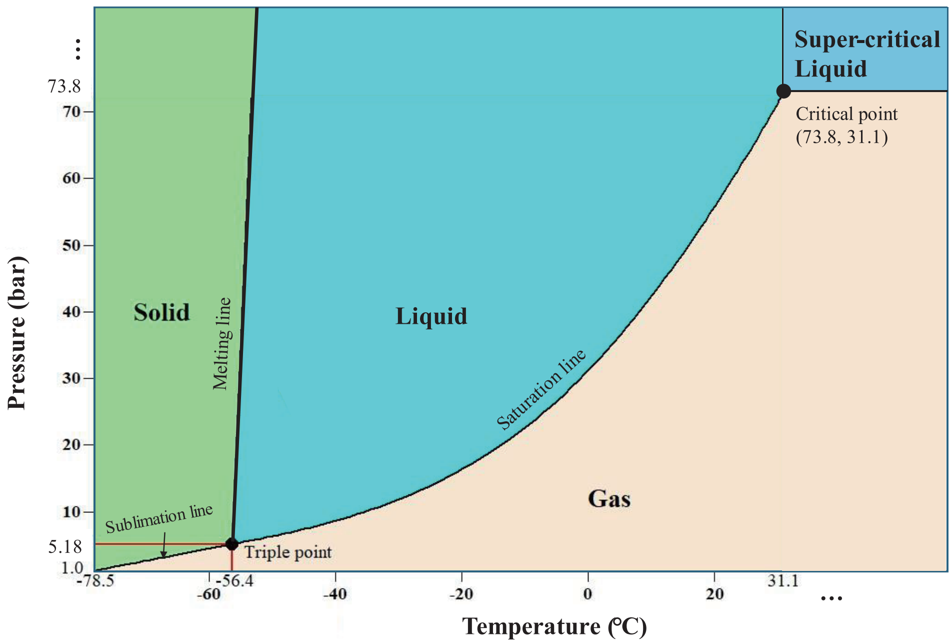

Notes: The diagram was generated using CHEMIX School 14.5®.

Figure 3. CO_2 phase diagram.

The variation of CO_2 cargo density with pressure and temperature is also a key factor in understanding the design principles of shipboard cargo systems. Figure 4 illustrates the relationship between CO_2 density, pressure, and temperature within the liquid and vapor phase regions. At constant pressure, density decreases with increasing temperature, while at constant temperature, density increases with increasing pressure.

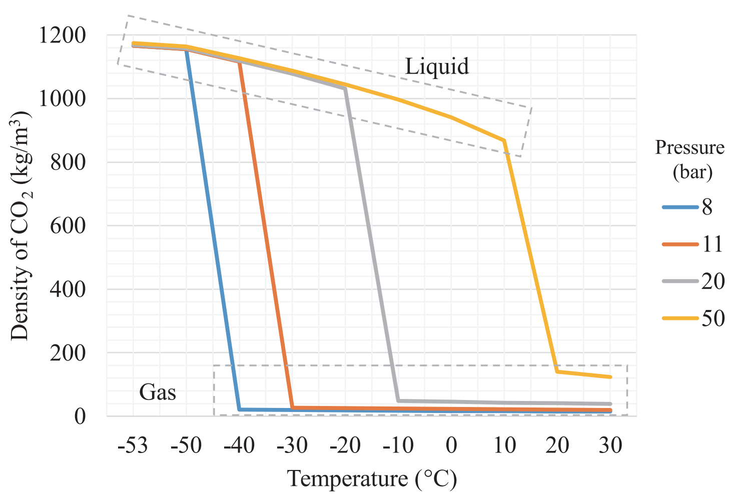

Figure 4. Relationship between pressure, temperature, and density of CO_2. (Wischnewski, 2007)

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3.2.2 Safety and design considerations

LCO_2 carriers are specifically designed to handle the unique thermodynamic properties of CO_2, particularly its triple point. These vessels typically employ IMO Type C tanks (pressure vessels) constructed from cryogenic-grade materials such as 9% nickel steel or high-strength alloys like P690QL2 to withstand both low temperatures and high pressures (American Bureau of Shipping [ABS], 2024; International Maritime Organization [IMO], 2016; Society of International Gas Tanker and Terminal Operators [SIGTTO], 2024). Safety systems are tailored to prevent cargo solidification, with redundant pressure controls, continuous gas monitoring, and specialized venting arrangements to avoid blockages, as mandated by the International Maritime Organization (IMO)'s *International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC Code) (Sections 17.21–17.22) and classification society rules (ABS, 2024; IMO, 2016). Additionally, the presence of impurities in captured CO_2—such as water, hydrogen sulfide, or sulfur oxides—requires careful material selection to mitigate corrosion risks.

The CO_2 phase diagram defines the conditions under which CO_2 remains in a liquid state while minimizing the risk of solid formation, which can lead to blockages or system damage. Accurate control of pressure and temperature is essential to ensure stable LCO_2 transport, with operational conditions typically chosen to avoid the triple point and prevent solid CO_2 formation under shipping pressures.

As pressure increases, the density of LCO_2 increases (Onyebuchi et al., 2018), but so does the cost of storage tanks due to the need for stronger, higher-pressure containment. Consequently, it is more cost-effective to ship LCO_2 at lower pressures within the liquid phase to balance the density and tank costs. While transporting LCO_2 at conditions near the triple point provides a favorable balance between CO_2 density and pressure, they come with inherent risks. Any fluctuation in pressure or temperature could lead to solid CO_2 formation (see Figure 3), which can damage cargo containment systems and disrupt sea transport. To mitigate this risk, most designs maintain a sufficient margin above the triple point during normal operations, see the existing ships in Table 1.

CO_2 purity plays a vital role in the phase behavior, as impurities such as nitrogen or oxygen can alter phase transition points (Goos et al., 2011), potentially shifting the triple point or lowering the temperature at which CO_2 remains in the liquid phase. This necessitates careful consideration of CO_2 purity during transport design to ensure system stability under varying conditions. For example, the Northern Lights CCS project imposes stringent CO_2 quality requirements, with a maximum impurity level of 0.2% (Northern Lights, 2024). These specifications ensure that CO_2 remains in a liquid state within the desired pressure and temperature ranges.

In accordance with the IMO IGC Code (IMO, 2016), the design of LCO_2 carriers must incorporate rigorous safety measures to address the specific hazards associated with CO_2's thermodynamic behavior. Given CO_2's proximity to its triple point under storage conditions, a low-pressure alarm is configured to activate at 0.5 bar above the triple point to avoid phase instability. If pressure falls to a critically low level, an automatic safety response is triggered: all cargo manifold liquid and vapor valves are closed, and cargo compressors and pumps are shut down to prevent solid CO_2 formation or equipment damage. To mitigate the risk of cargo solidification due to relief valve malfunctions in the open position, systems must include means for isolating cargo tank safety valves—a requirement unique to LCO_2 ships and not typically found on other types of gas carriers. Additionally, all materials used in cargo tanks and piping systems must be suitable for the lowest temperatures expected during service to ensure mechanical integrity. Although inerting is not required for LCO_2, proper gassing-up procedures after drying and pipeline pressurization are essential to prevent solidification. Continuous CO_2 monitoring is mandatory in enclosed spaces such as cargo holds, compressor rooms, and other areas where gas accumulation could pose an asphyxiation risk, thereby safeguarding crew safety and maintaining system integrity throughout the transport operation.

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In summary, the thermodynamic behavior of CO_2, especially near its triple point, dictates the operational envelope for safe and cost-effective maritime transport. Design strategies must carefully account for both phase behavior and gas purity, which together influence containment system specifications, safety protocols, and energy requirements. Importantly, the tanks at LCO_2 terminals and on-board ships must be compatible in terms of cargo pressure and temperature to ensure seamless transfer and handling.

3.3 Low-Pressure Cargo Systems: Advantages and Disadvantages

In the design of LCO_2 carriers, the selection of a suitable cargo containment pressure level is a critical decision that influences ship performance, system complexity, and commercial viability. While medium-pressure containment systems, typically operating in the range of 18–25 bar g, are currently more prevalent, as previously discussed, low-pressure systems operating between 5 and 10 bar g offer some potential benefits. However, these must be weighed carefully against a set of significant technical and operational challenges.

One of the main advantages of low-pressure cargo containment is the reduction in structural requirements for the cargo tanks. Lower design pressure results in thinner tank walls and lighter supporting structures, which can reduce both the weight and cost of materials, particularly when cryogenic-grade steels are used. For instance, a 4,300 m^3 LCO_2 tank designed for 10 bar g at –55 °C weighs 513 tonnes, compared to 651 tonnes for a 19 bar g design at –35 °C—a reduction of 21.2%. This simplification also extends to the construction process, potentially lowering shipyard labor hours and shortening construction schedules. From an operational standpoint, the energy required for CO_2 compression and pumping is lower under reduced pressure, which can translate into improved energy efficiency during cargo handling. To some extent, safety margins may also improve, as operating at lower pressures generally reduces the severity of failure modes such as rapid depressurization or tank rupture.

However, operating LCO_2 cargo containment systems in the 5–10 bar g range brings the storage conditions significantly closer to the triple point of CO_2. At or near the triple point, small fluctuations in pressure or temperature can cause phase changes between solid, liquid, and gaseous states. The formation of dry ice is particularly problematic. Maintaining a stable buffer above the triple point—typically by operating at least 6 bar g and around –50 °C—is therefore essential but demands precise pressure and temperature control.

The requirement to operate at such low temperatures adds further complexity to the vessel's cargo containment and management systems. More advanced thermal insulation is needed to minimize heat ingress, and in many cases, active refrigeration systems must be employed to maintain stable sub-cooled conditions throughout the voyage (Kim & Kim, 2024; Noh & Kang, 2025). These systems can increase both capital and operating costs and require additional space, electrical power, and maintenance resources. In warmer climatic conditions or during extended voyages, the refrigeration load may become particularly significant, affecting the vessel's energy efficiency and environmental footprint.

Furthermore, while medium-pressure systems benefit from greater industry familiarity and regulatory clarity, low-pressure containment for LCO_2 remains relatively novel. Fewer examples of commercial-scale implementation exist, which may pose additional hurdles in obtaining approval from classification societies and flag state authorities. The limited availability of commercial components optimized for low-pressure LCO_2 service may also affect system reliability and lifecycle maintenance planning.

In summary, low-pressure cargo containment systems offer notable benefits in terms of reduced structural weight, construction simplicity, and lower energy requirements. However, the thermodynamic risks associated with operating near the triple point of CO_2—alongside the demands for advanced thermal

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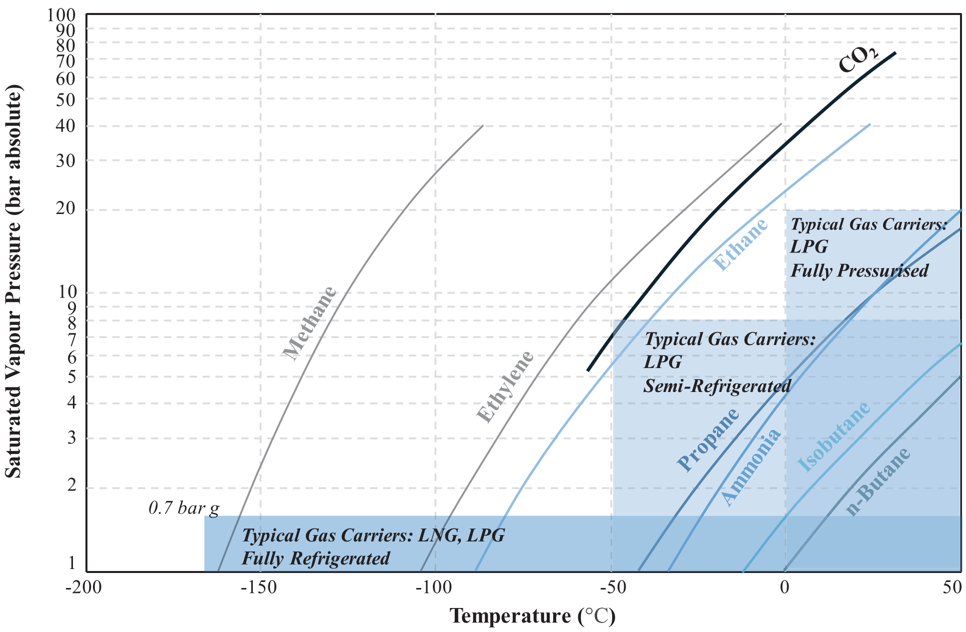
management and precise system control—present non-trivial challenges. A careful techno-economic assessment is therefore essential to determine the suitability of low-pressure containment for any given LCO_2 transport scenario, especially when long distances, warm climates, or high-capacity requirements are involved.

3.4 Adapting LCO_2 Carriers for Multi-Gas Transport

Given the potential economic and operational advantages of multipurpose vessels in addressing market uncertainties, it is worth exploring whether LCO_2 carriers could be designed or adapted to also transport other liquefied gases, such as ammonia (NH_3) or LPG. Such flexibility could enhance asset utilization, reduce idle time, and improve return on investment. However, this possibility requires careful evaluation of differences in thermophysical properties, material compatibility, safety requirements, and regulatory compliance for each cargo type.

Regarding the thermodynamic operating ranges of various gases, Figure 5 presents a comparison of the saturated vapor pressure curves of CO_2 and several common liquefied gases—namely methane, ethylene, ethane, propane, ammonia, and butane—highlighting key differences in their phase behavior and associated operational requirements (Babicz, 2015; Bond, 2024). The comparison indicates that transporting methane and ethylene using LCO_2 carrier systems is impractical, as their storage in ships requires significantly lower pressures and temperatures: large liquified natural gas (LNG) carriers typically operate at below 0.7 bar g, while liquified ethylene carriers are designed for a maximum pressure of approximately 4 bar g. In contrast, gases such as ethane, ammonia, and LPG (propane and butane) exhibit thermodynamic compatibility, suggesting potential for shared or adaptable cargo system designs. From the opposite perspective, Figure 5 indicates that existing gas carriers cannot be used to transport LCO_2, meaning that repurposing such vessels for LCO_2 service is impractical.



Data source: WÄRTSILÄ and American Bureau of Shipping (ABS). (Babicz, 2015; Bond, 2024)

Figure 5. Comparison of temperature-pressure curves of liquified gases and their typical operating range.

3.4.1 Transporting liquefied ethane

The primary use of ethane (C_2H_6) is in the chemical industry in the production of ethylene (C_2H_4), which in turn is used to produce polyethylene, polyvinyl chloride (PVC), ethylene glycol, and styrene (Lloyd's Register Marine, 2014). Semi-refrigerated ethane carriers are typically designed for operating pressures in the range of 4–7 bar g, with cargo tanks maintained at approximately –50 °C. These conditions are compatible with those of low-pressure LCO_2 carriers (6–10 bar g). This overlap in thermodynamic conditions indicates that the transport of ethane using LCO_2 carriers is technically feasible from a containment perspective.

However, further considerations must be addressed when adapting LCO_2 carriers for ethane service. Ethane is a flammable hydrocarbon, unlike CO_2, and its safe transport requires adherence to more stringent safety standards. These include provisions for gas detection, explosion protection, and the use of compatible materials in cargo handling systems to mitigate fire and chemical risks. Structural integrity, insulation performance, and materials must also be validated to ensure compliance with regulatory frameworks such as the IMO IGC Code (IMO, 2016).

3.4.2 Transporting liquefied ammonia

Ammonia (NH_3), a key candidate for hydrogen-based energy systems, shares some operational similarities with CO_2 that could make it a viable alternative cargo for LCO_2 carriers. NH_3 can be stored at –33 °C at atmospheric pressure or at moderate pressures (8–10 bar g) under atmospheric temperature (Fan et al., 2022). The existing tank design of LCO_2 carriers could theoretically accommodate NH_3, provided the cargo system is compatible with ammonia's chemical properties.

However, several technical challenges must be addressed. Ammonia's high toxicity necessitates stricter gas detection and leak prevention measures than those required for CO_2, which is non-flammable but poses asphyxiation risks. For instance, NH_3-compatible carriers employ double-walled piping and enhanced sealing systems to prevent accidental releases. Material compatibility is another concern, as ammonia can induce stress corrosion cracking in copper-based alloys and certain steels (Elishav et al., 2021). Thus, adapting an LCO_2 carrier for NH_3 transport would require verification of material suitability, potentially necessitating upgrades to piping and valve systems.

3.4.3 Transporting liquefied petroleum gas

LPG, primarily composed of propane (C_3H_8), butane (C_4H_{10}), and isobutane (C_4H_{10}), operates within a temperature and pressure range that partially overlaps with that of LCO_2. LCO_2 carriers could therefore be suitable for LPG transport.

The primary challenge lies in the flammability of LPG, which introduces additional safety considerations absent in CO_2 transport. LPG carriers are equipped with inert gas systems to maintain a non-flammable atmosphere in cargo tanks and void spaces, a feature not typically included in LCO_2 carriers. While the structural design of LCO_2 carriers may suffice, operational protocols would need significant revisions to meet the safety standards for flammable gases.

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Overall, the adaptation of LCO_2 carriers for transporting other liquefied gases is limited by a range of technical, regulatory, and economic factors. The pressure–temperature profiles of alternative cargoes—such as ethane, ammonia, and LPG—often diverge from the design parameters optimized for CO_2, requiring reassessment of structural integrity, thermal insulation, and reliquefaction systems. Material compatibility presents another constraint, particularly for ammonia, which introduces specific corrosion risks that must be addressed through careful material selection. In addition, compliance with gas-specific safety regulations—such as inerting requirements for ethane and LPG, or enhanced leak detection systems for NH_3—adds further complexity and costs, potentially undermining economic feasibility. While thermodynamic analyses suggest that these gases could theoretically be transported within defined operating windows, the technical modifications needed to accommodate them are non-trivial. Approaches such as modular cargo handling systems and the use of corrosion-resistant materials may offer pathways to increased flexibility. However, these adaptations must be carefully evaluated against the commercial realities of CO_2 shipping, which remains a niche and project-specific sector.

3.5 LCO_2 Carriers with Direct Ocean Injection Capability

In recent years, the concept of using LCO_2 carriers not only for transport to geological storage sites but also for direct injection (DI) into the deep ocean has attracted increasing attention (Al Baroudi et al., 2021; DNV, 2025; Skjæveland, 2023). This concept involves designing ships capable of both storing LCO_2 under cryogenic conditions and discharging it directly into the deep sea at appropriate depths, where CO_2 is more stable due to high pressure and low temperature. Notably, the integration of DI on LCO_2 carriers is more suitable for high-pressure designs (approximately 40–50 bar and temperatures above 0 °C), as elevated pressure facilitates the injection process.

From a technical perspective, implementing a DI function requires significant modifications to the conventional LCO_2 carrier design. Most notably, the vessel must be equipped with a deep-sea injection system, including high-pressure pumps, reinforced discharge pipelines, and dynamic positioning systems to maintain operational stability during injection. The injection might target depths exceeding 3,000 metres (World Ocean Review, 2024), where the ambient pressure exceeds the saturation pressure of CO_2 at near-seabed temperatures, promoting the formation of negatively buoyant CO_2 or hydrate phases that are less likely to return to the ocean surface.

Operationally, direct ocean injection may offer advantages in flexibility and cost. By avoiding the need for onshore or offshore unloading facilities or pipeline networks, ships with onboard injection systems could enable the deployment of offshore CCS projects in remote ocean regions or in countries lacking geological formations suitable for long-term storage.

However, the implementation of direct ocean injection raises significant environmental, regulatory, and ethical concerns. The long-term ecological impacts of deep-sea CO_2 injection remain uncertain, particularly regarding ocean acidification, disruption of deep marine ecosystems, and changes in biogeochemical cycles (Barry et al., 2004; Seibel & Walsh, 2001).

The current interpretation of the London Protocol, which governs marine pollution, places strict limitations on the deliberate disposal of CO_2 into the marine environment. While amendments have been proposed to allow for the export of CO_2 for sub-seabed geological storage (IMO, 2019), the use of direct ocean injection remains controversial and unregulated. Consequently, the commercial deployment of LCO_2 carriers with injection capability is unlikely to proceed without significant changes in international law, as well as comprehensive environmental impact assessments and long-term monitoring strategies.

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In summary, the integration of a direct ocean injection function into LCO_2 carriers is technically feasible and may provide a flexible offshore sequestration option, particularly for nations without immediate access to geological storage infrastructure. Nevertheless, such applications face considerable regulatory and environmental hurdles. Further research and international dialogue are required to assess the viability of this approach as part of a broader carbon management strategy.

4 CONCLUSIONS

The transition to a low-carbon economy necessitates scalable and flexible solutions for CO_2 transport if CCS is to be widely implemented, with maritime shipping playing a pivotal role in bridging the gap between emission sources and storage sites. This study highlights the unique challenges and opportunities in designing LCO_2 carriers, emphasizing the importance of thermodynamic stability, safety protocols, and economic viability. Key conclusions include:

- Thermodynamic and Design Considerations: The phase behavior of CO_2, particularly near its triple point, demands precise control of pressure and temperature in cargo systems to prevent solidification and ensure safe transport. Medium-pressure regimes (18–25 bar g) currently dominate, but low-pressure systems (6–10 bar g) offer potential cost savings despite increased technical complexity.
- Fleet Scalability: Existing LCO_2 carriers, primarily small-scale vessels for industrial use, are insufficient for CCS-scale operations. New vessels with capacities exceeding 20,000 m^3 are under construction, reflecting the growing demand for large-volume transport.
- Multifunctional Cargo Systems: While LCO_2 carriers could theoretically transport other liquefied gases (e.g., ethane, ammonia, and LPG), material compatibility, safety requirements, and regulatory hurdles limit their practicality without significant design modifications.
- Direct Ocean Injection: Technically feasible but ethically and legally contentious, this approach requires rigorous environmental impact assessments and international regulatory alignment before deployment.
- Regulatory and Safety Frameworks: Compliance with the IMO IGC Code, classification society rules, and relevant industry standards is essential to mitigate risks, ensure operational safety, and maintain the overall integrity of LCO_2 transport systems.

In summary, the successful integration of LCO_2 shipping into the CCS supply chain hinges on advancing cargo system technology, fostering cross-sector collaboration, and addressing unresolved environmental and regulatory questions.

Future research should prioritize optimizing pressure-temperature regimes, exploring modular designs, and assessing the lifecycle impacts of maritime CO_2 transport to support global decarbonization goals. For LCO_2 carriers with DI capability, research must clarify long-term ecological impacts through modelling and pilot studies, while addressing regulatory barriers. Multidisciplinary efforts that integrate environmental, legal, and techno-economic perspectives will be critical to determining the viability of DI for LCO_2 carriers.

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ABBREVIATIONS

ABS	American Bureau of Shipping
CCS	Carbon capture and storage
CCUS	Carbon capture, utilization, and storage
CO_2	Carbon dioxide
DI	Direct injection
FSIU	Floating storage and injection unit
GHG	Greenhouse gas
IEA	International Energy Agency
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
IOGP	International Association of Oil & Gas Producers
LCO_2	Liquefied carbon dioxide
LNG	Liquified natural gas
LPG	Liquified petroleum gas
NH_3	Ammonia
PVC	Polyvinyl chloride
UK	The United Kingdom

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