ABS

Offshore Floating CO_2 INJECTION FACILITIES

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CCS BACKGROUND

The Paris Agreement, adopted in 2015 by 196 international parties under the United Nations Framework Convention on Climate Change (UNFCCC), aims to limit the global temperature increase to less than 2° C, with an ideal target of no more than a 1.5° C increase above pre-industrial levels. To reach this objective, many governments, regulatory bodies and industries are working to stabilize and reduce greenhouse gas (GHG) emissions. For example, the Intergovernmental Panel on Climate Change (IPCC) has outlined several potential scenarios for limiting temperature rise, all of which emphasize how carbon capture and storage (CCS) could help.

According to the International Energy Agency (IEA), around 75 percent of annual GHG emissions are created by the global energy sector. In alignment with the IPCC's Sixth Assessment Report, the IEA introduced the Net Zero Emissions by 2050 Scenario (NZE) to guide the energy industry toward achieving net-zero GHG emissions and help limit global temperature rise. Highlighting the importance for international cooperation in the deployment of clean energy technologies and energy efficiency measures, the NZE scenario aims to help the industry meet key U.N. Sustainable Development Goals, including universal energy access by 2030.

REGULATIONS

The offshore industry's emerging CCS sector is shaped by a complex regulatory landscape. Regulatory bodies are developing carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, to incentivize the reduction of carbon emissions. These mechanisms aim to internalize the environmental costs of emissions and promote investment in CCS technologies. Financial incentives and subsidies could play a key role in accelerating the deployment of CCS projects. Some governments and international bodies offer grants, tax credits and low-interest loans to offset the high initial costs associated with these technologies. The regulatory frameworks governing CCS encompass permitting processes, safety standards and environmental impact assessments, all helping to promote the safe and effective operation of CCS facilities. These are still evolving to address the unique challenges of offshore applications. International collaboration and standards have an important part to play in harmonizing regulations and fostering innovation. Organizations such as the IEA and the Global CCS Institute work to develop best practices and facilitate knowledge sharing among countries. This collaborative approach helps to establish consistency across standards and fosters the global adoption of CCS technologies.

SHIFT FROM CURRENT CO_2 ENHANCED OIL RECOVERY (EOR) TO DEDICATED CO_2 STORAGE MODEL

Enhanced Oil Recovery (EOR) could play a significant role in the future of the CCS sector, offering both opportunities and challenges for carbon mitigation. The EOR process involves the injection of carbon dioxide (CO_2) into oil fields that are experiencing lower lift pressure or require external intervention to continue production. The injection of CO_2 re-establishes the necessary pressure differential, facilitating the extraction of the remaining crude oil. While EOR projects are primarily aimed toward maximizing oil production, they can also serve as a roadmap for the long-term storage of captured CO_2. The established infrastructure, expertise and regulatory frameworks of EOR projects are conducive to large-scale CO_2 storage and transportation.

According to the IEA, more than 10 million tonnes (Mt) of CO_2 are injected annually for storage across 10 commercial-scale sites. However, with upcoming projects, this storage capacity could rise to around 615 Mt of CO_2 per year by 2030.

The use of CO_2 in EOR is expected to drop significantly by 2030. This shift is illustrated in Figure 1 and is driven by various factors, including regulatory mandates encouraging the development of dedicated CO_2 storage – as demonstrated in Canada – as well as the growing role carbon capture, utilization and storage (CCUS) value chain could play in enabling certain economies, such as Norway, the United States, and the United Kingdom, to transition to net-zero emissions.

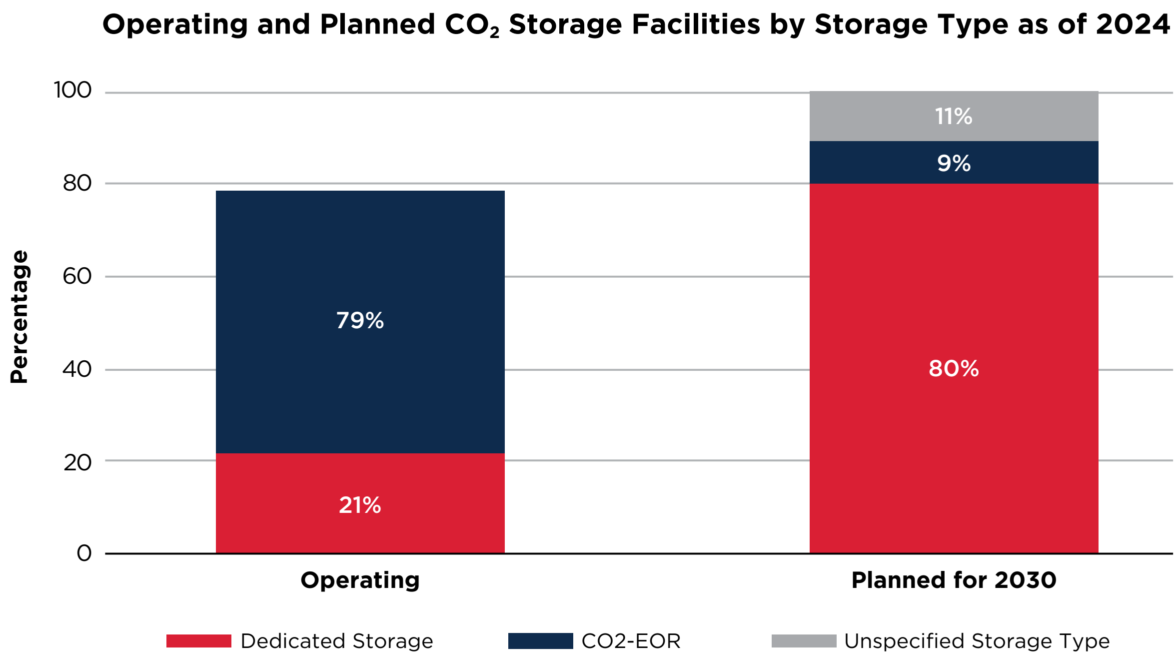

Figure 1: Operating and planned CO_2 storage facilities by storage type as of 2023 (1)

CCS NETWORK BUSINESS MODEL

The carbon capture and storage (CCS) business model encompasses a wide range of elements, including capture facilities, transportation infrastructure, storage sites and regulatory compliance mechanisms. The collecting hub, strategically positioned for logistical optimization, serves as a central aggregation point for consolidating CO_2 from several sources before it is transported to storage sites, usually via pipelines. Revenue streams include fees for capture, transportation and storage services, as well as potential earnings from carbon credits or government incentives. The success of this model relies on technological advancements, regulatory backing and market demand, highlighting its role in mitigating carbon emissions and promoting sustainable energy practices.

The concept of using a floating injection hub for offshore CO_2 storage addresses scenarios where traditional pipeline connections are not economically viable. The core concept involves collecting emitted CO_2, liquefaction at the terminal, and transporting it to the injection unit, similar to the inland model. However, the injection portion of the floating model prioritizes mobility, connecting the inland collection hub and the injection hub by liquefied CO_2 (LCO_2) carriers instead of pipelines.

CO_2 STORAGE RESERVOIRS

The potential for offshore CO_2 sequestration involves taking advantage of existing reservoirs – typically either depleted oil and gas reservoirs or saline aquifers. Depleted oil and gas reservoirs are underground formations in which hydrocarbons have previously accumulated but have since been exploited to a stage where most of the economically recoverable oil or gas has been extracted. A saline aquifer is a subsurface geological formation containing high levels of dissolved salts, such as sodium chloride, in the water, rendering it economically unviable for extracting fresh water. The specific strata referred to as "aquifers" consist of porous and permeable rocks saturated with water. These aquifers are frequently examined as potential reservoirs for CO_2 injection due to their geological characteristics and their capacity to securely retain CO_2 over prolonged periods of time.

When considering the use of either type of reservoir, cap rock integrity is crucial for ensuring safe long-term CO_2 storage. Cap rock acts as a natural barrier, preventing CO_2 from escaping the storage site. Detailed analysis of cap rock properties, such as porosity and permeability, can enhance the understanding of storage site suitability and mitigate potential leakage risks. Figure 2 shows some reservoir types found in North America and their estimated storage capacities. Given these estimates, it is evident that saline aquifers have the most potential in terms of storage capacity, which means the volume of business scale can be maximized.

Table 1: CO_2 sequestration potential of different reservoirs in North America (2)

Reservoir Types	Estimated Storage Capacity (Gt)	Reservoir Integrity
Depleted Oil and Gas Reservoir	186 - 232	High
Saline Aquifer	2,379 - 21,633	The Highest
Total	2,565 - 21,865	

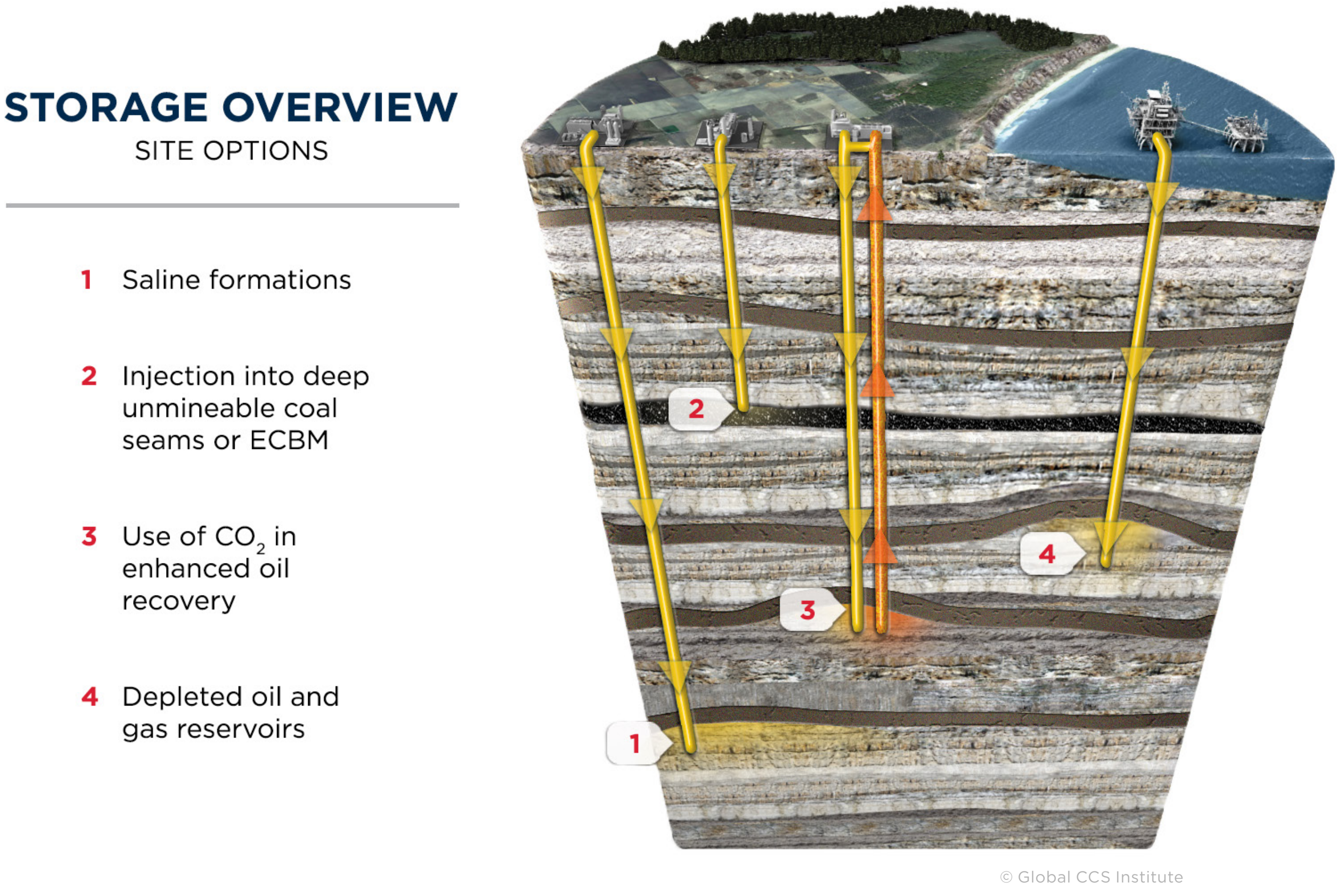

Figure 2: CO_2 Storage Overview for Site Options

TRANSPORT OVERVIEW

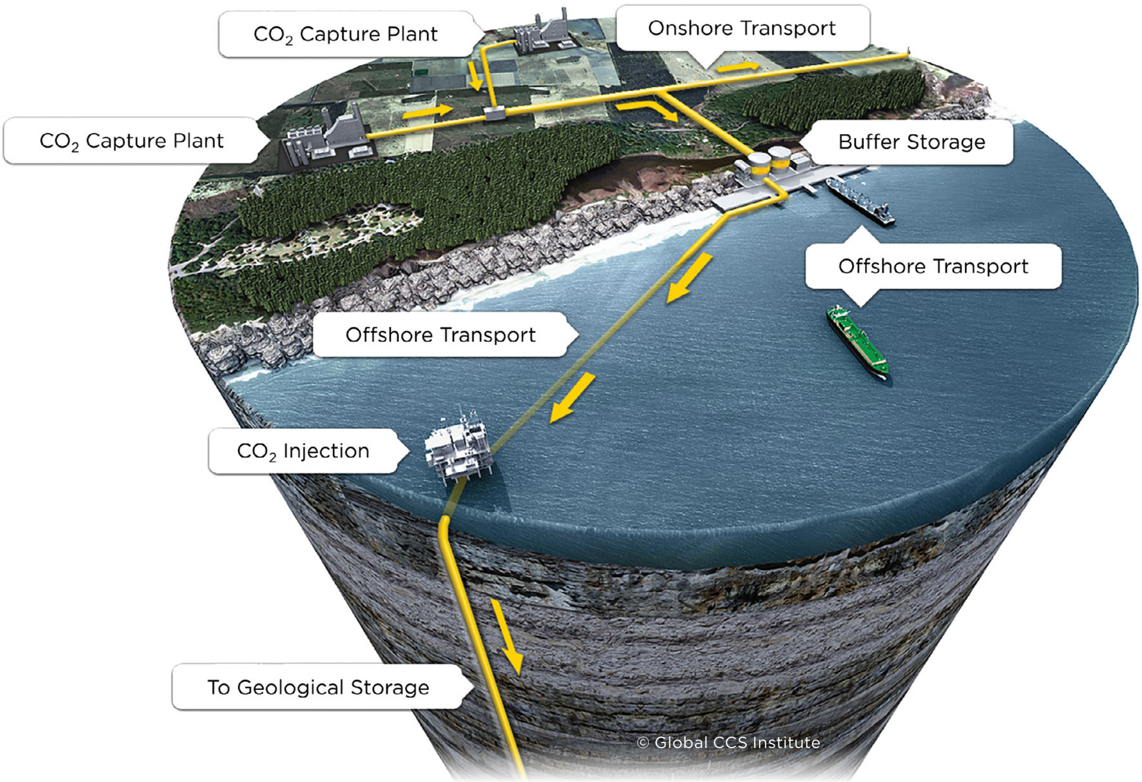

Figure 3: CO_2 Transport Overview

CURRENT GLOBAL OFFSHORE CO_2 STORAGE PROJECTS

The total counts of current global offshore CO_2 storage projects in Figure 3 originated in a publication by the Center of International Environmental Law (CIEL). While not comprehensive, this compilation represents the most reliable publicly accessible data on existing and proposed offshore CCS projects as of November 2023.

CIEL analyzed that, as of August 2023, there were at least 57 proposals for offshore carbon sequestration worldwide, the vast majority of which are planned for operation by 2030.

Table 2: Offshore Carbon Capture and Storage Projects from CIEL Appendix (3)

Country	Project
Australia	• Bayu-Undan CCS • Bonaparte CCS Assessment G-7-AP • Burrup CCS Hub • Santos Bonaparte CCS Assessment • CarbonNet Project • CStore1 Project • Reindeer CCS • South East Australia CCS Hub
Belgium	• Antwerp@C
Brazil	• Petrobras Santos Basin Pre-Salt Oil Field CCS
Bulgaria	• ANRAV
China	• CNOOC Enping Offshore CCS Project • Daya Bay CCS Hub • Ledong CO_2-EOR

Country	Project
Denmark	• Bifrost • Project Greensand
France	• CalCC • K6 Program
Greece	• Prinos CCS
Indonesia	• Pertamina Exxon Indonesia Hub
Ireland	• Ervia Cork CCS
Italy	• Ravenna CCS Hub
Japan	• Japanese Advanced CCS Projects
Malaysia	• Petronas Kasawari CCS project • Lang Lebah CCS project
Netherlands	• Aramis • L10 Offshore CCS • Porthos • NoordKaap
Norway	• Sleipner • Snøhvit • Barents Blue/Polaris Carbon Storage • Errai CCS • Kollsnes DAC Facility • Luna • Northern Lights • Smeaheia • Trudvang
Poland	• Go4ECOplanet
South Korea	• Donghae CCS project
Sweden	• Slite CCS
Thailand	• PTTEP Arthit CCS
United Arab Emirates	• Ghasha Concession Fields
United Kingdom	• Acorn • Bacton Thames Net Zero Initiative • Caledonia Clean Energy Project • Cory EfW Plant CCS • East Coast Cluster • H21 North of England • HyNet North West • Medway Hub CCS • Morecambe CCS Hub • Sullom Voe Terminal CCS • Viking CCS Network
United States	• Bayou Bend CCS • Cameron Parish CO_2 Hub • Coastal Bend CCS • Corpus Christi Offshore • Houston Ship Channel CCS • Project Lochridge

WHAT IS AN OFFSHORE CO_2 INJECTION HUB?

When captured CO_2 is ready to be moved from the capture facility into long-term storage, there are several possible transport methods that can be used. Currently, the two most commonly considered methods for transporting CO_2 to the storage reservoir are pipelines and marine transport via shipping vessel. In cases where pipeline transport may not be feasible – for example, longer distance from the shore, difficult subsea terrain, business risks of high capital expenditures (capex) of pipeline installation, etc. – a carrier vessel can transport the LCO_2 to an offshore hub for injection into storage.

Because the CO_2 needs to meet the specific conditions required by the reservoir before injection, and buffer storage may be needed to facilitate continuous injection, there are several possible scenarios for the arrangement of the technology and buffer storage facilities needed for offshore injection of CO_2.

The three scenarios outlined below are considered the most technically feasible and cost-effective options for offshore injection. All scenarios outlined are based on the assumption that pure CO_2 conditions are obtained at an onshore terminal or storage facility, and then the conditioned CO_2 is loaded onto the LCO_2 carrier. This implies that there is no need for purifying facilities onboard the injection unit for any of the scenarios described below.

SCENARIO 1: CO_2 CARRIER DIRECT INJECTION

In this scenario, CO_2 is injected directly from the LCO_2 carrier into the seabed well upon arrival at the injection site. While costly buffer storage is not utilized in the direct injection model, it does call for a conditioning facility to adjust the CO_2 to the pressure and temperature required for injection via an injection riser. This conditioning facility can be either on board the carrier or on a fixed platform at the injection site. This particular type of injection carrier vessel will eliminate the need for large-scale offshore structures. However, the savings from bypassing the buffer storage unit will be offset by the need for at least one additional vessel with buffer storage of larger capacity than the injection carrier.

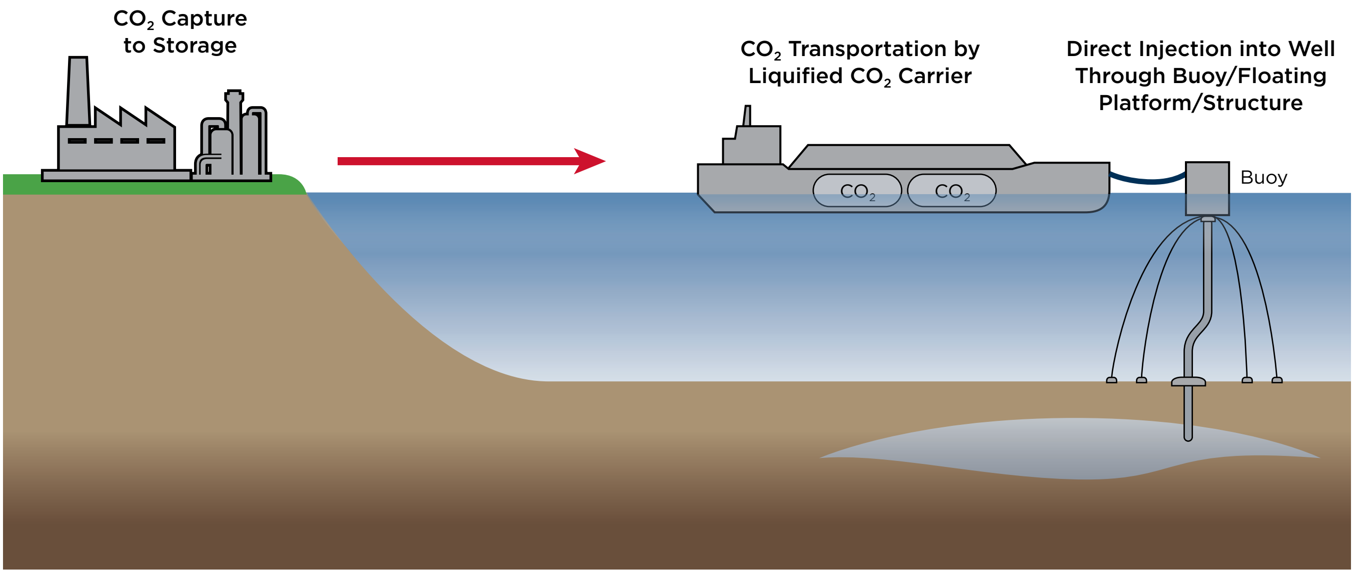

Figure 4: CO_2 carrier direct injection

SCENARIO 2: CO_2 CARRIER TO PLATFORM INJECTION FACILITY WITHOUT STORAGE

This scenario utilizes a platform equipped with conditioning and injection systems at the injection site. The CO_2 can be offloaded directly on to the platform upon arrival of the LCO_2 carrier. This allows CO_2 to be injected into the well through the platform, which can be either a permanent fixture on the seabed or a moored floating structure. A significant difference between direct injection from LCO_2 carriers and the carriers used in this scenario is that the latter may or may not require the conditioning and injection facilities to be on board each vessel. However, similar to direct injection, the injection facility is assumed to lack buffer storage. As a result, an additional carrier with a larger capacity than the injection carrier would be needed in this scenario.

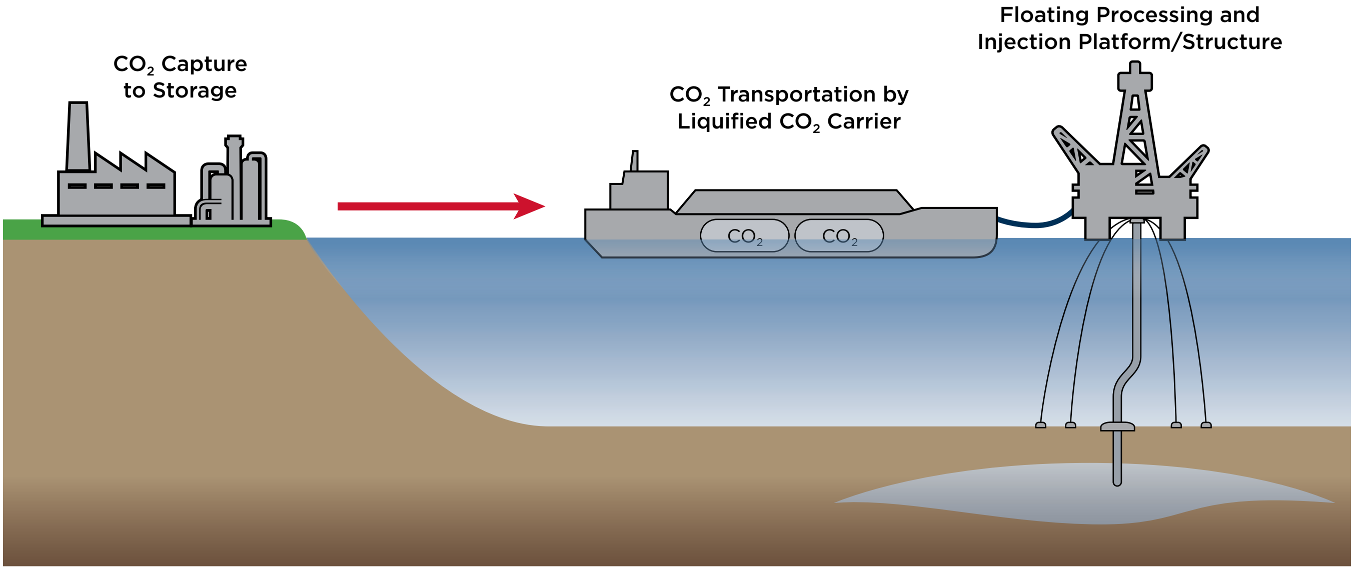

Figure 5: CO_2 carrier to platform injection facility without storage

SCENARIO 3: CO_2 CARRIER TO INJECTION FACILITY WITH BUFFER STORAGE

In this scenario, the injection facility is equipped with buffer storage, allowing the offloaded LCO_2 to be stored directly in tanks located within the floating unit before injection. The unit is also fitted with conditioning process machinery onboard to prepare the LCO_2 before injection, thus relieving the LCO_2 carriers from the burden of onboard injection and conditioning equipment. The injection facility may take the form of a fixed platform positioned atop the injection well or a moored structure at the site.

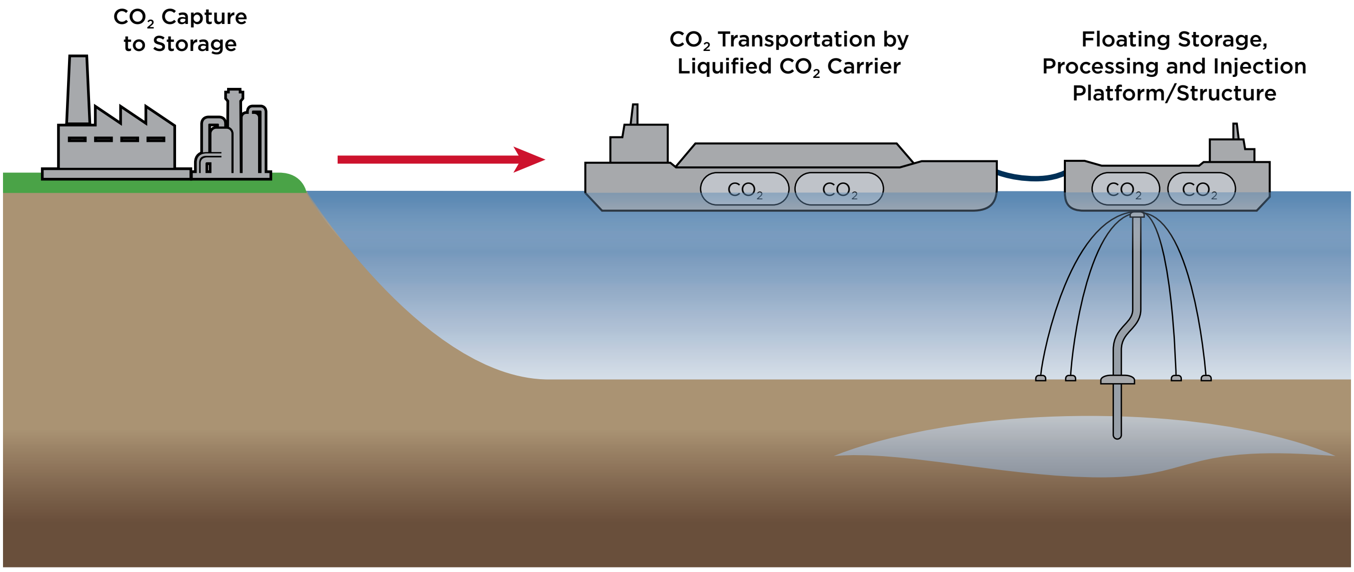

Figure 6: CO_2 carrier to injection facility with buffer storage

CONCEPT OF FSIU

The conceptual CO_2 floating storage and injection unit (FSIU) is designed as a vessel tailored for the temporary storage and subsequent injection of CO_2 into wells for geological storage, such as depleted oil and gas reservoirs or deep saline aquifers. The FSIU serves as a dual-purpose injection hub and offshore terminal, managing buffer storage and conditioning functions before the injection process. Drawing parallels with established maritime structures like floating production, storage and offloading (FPSO) or floating liquefied natural gas (FLNG) facilities, the FSIU capitalizes on established loading and injection operational expertise derived from the oil and gas production industry.

This unit facilitates the offloading of LCO_2 cargo into storage, followed by a conditioning process to meet injection requirements before being introduced into the seabed reservoir via subsea flexible piping. Structured in the form of a vessel, the terminal offers ample buffer storage space compared to a platform, ensuring safe storage conditions in the ocean environment. It is engineered for permanent mooring at offshore sites with the possibility of relocation as necessitated by specific project requirements.

LIMITATIONS OF SCENARIOS 1 AND 2

Considering the three injection scenarios above, it becomes evident that another vessel with a larger capacity may be needed in the absence of offshore storage to maintain continuous injection. Additionally, numerous vessels frequently connecting to and disconnecting from the injection equipment will create additional safety concerns that would need to be addressed. For a specific business model, such as the one described in scenario 3, the most suitable approach would involve having buffer storage in both the offshore injection unit and the LCO_2 vessels themselves. The concept of FSIUs is gaining traction in the industry. Research and cost analyses indicate that having buffer storage near the well is the most cost-effective solution, even for large-scale CCS business models, as it allows for shorter LCO_2 offloading times and facilitates more frequent shipping.

OUTLINE OF FSIU FUNCTIONALITY

CO_2 is intended to be transported via specialized LCO_2 carriers to the FSIU, which is moored near the permanent storage site. Before shipping, CO_2 is collected from various emitters, then conveyed to and stored in a strategic onshore terminal hub. The quality of CO_2 from different emitters across industries may vary due to impurities, which requires conditioning and liquefaction prior to loading onto the LCO_2 carrier. Generally, FSIUs are designed to carry liquid CO_2 within a specified impurity threshold, which differs from project to project, helping to smooth operations by avoiding issues caused by deviations from the system design parameters.

Conditioned CO_2 intended for loading onto an LCO_2 carrier will be transferred from the port terminal via loading arms or other mechanisms capable of withstanding high pressure and cryogenic temperatures. Given current technological capabilities and the lack of comprehensive data in the CCS industry, LCO_2 is likely to be shipped under low- to medium-pressure conditions ranging from 6–19 bar at -21°C to -54°C, which is commercially matured in land-based industries. The FSIU will be designed to be compatible with the CO_2 pressure range required by the LCO_2 carriers.

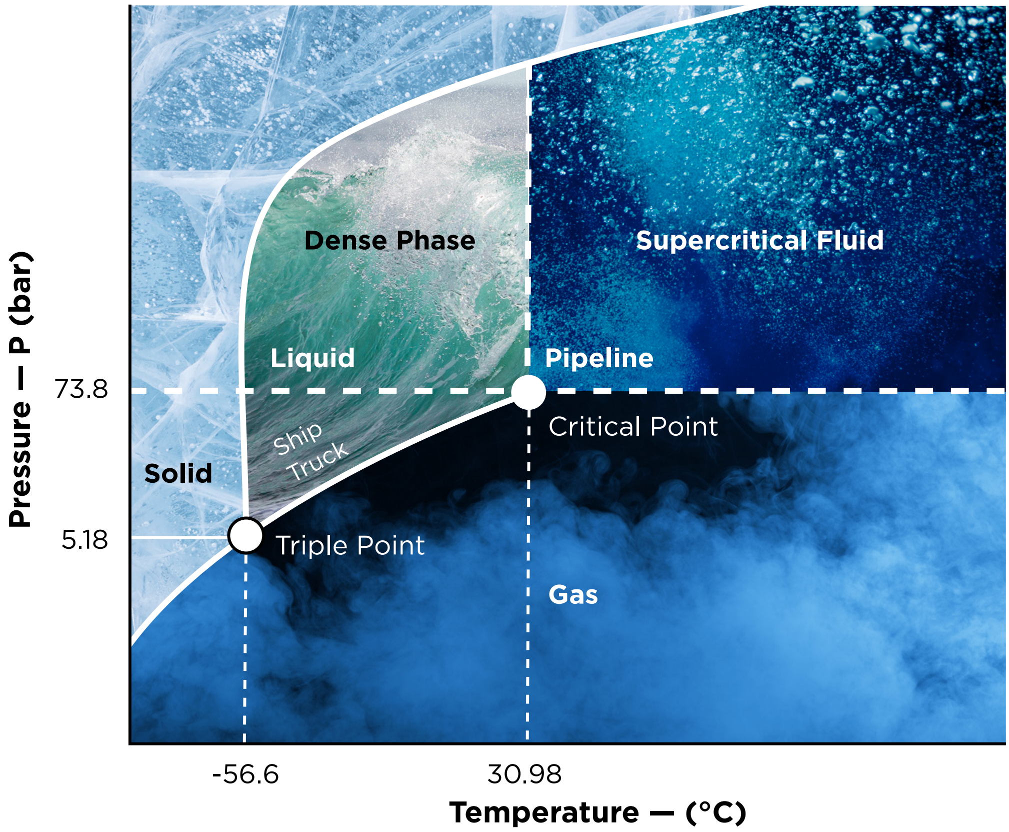

Figure 7: Phase Diagram of CO_2 with pressure areas of transportation Original

Upon arrival to the FSIU, the LCO_2 carrier will offload the CO_2 via a mechanism such as a floating flexible hose or loading arms. Subsequently, the offloaded liquid CO_2 will undergo secondary conditioning processes involving heating and pressurizing to achieve the desired injection condition – typically the supercritical phase of CO_2. By reaching supercritical condition, the process mitigates the risk of CO_2 hydrate formation, which can obstruct the system, leading to critical operational challenges.

The designed pressure and temperature parameters will vary based on specific project requirements, reservoir conditions, injection duration and the evolving pressure within the reservoir over time. Injection operations will be executed using an injection pump, after which supercritical CO_2 will travel through injection risers installed at the unit. These risers are connected to a subsea Christmas tree to manage injection into the storage reservoir in a controlled manner, helping ensure the integrity and safety of formation and well.

LIQUID CO_2 OFFLOADING TECHNOLOGY

Offloading technology is crucial in facilitating the CO_2 value chain for shipping, as it is the linchpin connection between CO_2 carriers and CO_2 injection hubs. However, offshore offloading remains unproven and has yet to be implemented on a commercial scale. Offloading occurs through a flexible hose linking the cargo tank of the LCO_2 carrier to the buffer storage tank of the FSIU. The hose is designed to withstand high-pressure, low-temperature conditions with limited heat transfer rates. FLNGs often use loading arms for side-by-side offloading, minimizing temperature losses compared to floating hoses and ensuring efficient transfer of liquid CO_2 while maintaining cryogenic temperatures. Maintaining cryogenic temperatures in floating hoses is challenging, but solutions such as advanced insulation materials or active cooling systems can help mitigate temperature losses during offloading. Loading arms and cryogenic hoses can be employed for side-by-side offloading of liquid CO_2, offering stability and ease of connection and disconnection. While this method is widely used in other marine operations, both side-by-side and tandem offloading configurations are considered viable for CO_2 transfer, with the preferred approach determined by site-specific factors. Tandem mooring, despite certain challenges, remains a viable option, requiring detailed feasibility studies and safety measures to help ensure successful operations. An offloading buoy with a connecting riser offers flexibility and reduces operational risks, allowing for continuous offloading and adaptation to various offshore conditions.

Prior to transferring liquid CO_2 from the carrier, storage tanks of the FSIU need to be maintained with appropriate temperature and pressure to prevent dry ice formation. Offloading the liquid CO_2 into the storage tanks replaces the vapor CO_2, with the displaced vapor returning to the LCO_2 carrier via a vapor return line to maintain pressure in the offloading tank. Tank pressure and filling rate are monitored remotely by the control system. Robust safety protocols are essential for offloading operations, including emergency shutdown systems, regular inspections, and adherence to industry standards. Enhancing offloading efficiency can be achieved through automated monitoring systems, optimized flow rates, and the use of advanced materials for hoses and loading arms. Using advanced materials for hoses and loading arms can improve durability and reduce heat transfer, helping ensure the integrity of the offloading process. Real-time monitoring systems can track temperature, pressure, and flow rates during offloading operations, enhancing safety and efficiency.

LCO_2 STORAGE TANK TECHNOLOGY

Storage tanks shall be designed to withstand the specified pressure, temperature and other design conditions of the intended cargo to help ensure safety. Therefore, LCO_2 storage tanks are constructed with materials and insulation capable of sustaining the liquid state of CO_2. The design conditions of the storage tanks are contingent upon the pressure and temperature requirements of the stored cargo. If the storage condition for LCO_2 falls within either the medium-pressure (14 bar at -21°C) or low-pressure (6 bar at -40°C) range, the tank must be designed accordingly to meet these specifications.

Appropriate material selection is essential to help ensure durability and resistance to corrosion, with consideration given to the wall thickness to withstand pressure and prevent material failure. Additionally, suitable insulation around the tank's exterior is selected based on functionality, ease of maintenance and its own life cycle.

In line with current practices, the most appropriate tank type is the Type-C tank, characterized by its cylindrical, bi-lobe form and renowned for its robust design and high-pressure capacity as a liquefied gas storage solution. Liquid CO_2 tanks must be equipped with systems to handle and manage boil-off gas (BOG) to prevent overpressure, loss of pressure and maintain temperature control. Solutions can include refrigeration plants or controlled discharge systems, although controlled discharge may require careful consideration. To uphold safety standards, a tank pressure protection system with pressure relief devices is essential. This system effectively manages overpressure within the tank by venting excess gas into a safe area.

The LCO_2 will be discharged to the CO_2 injection unit by a submerged CO_2 discharge pump located on the bottom of the storage tank or other suitable means.

CONDITIONING TECHNOLOGY

The target injection condition of the CO_2 must consider the desired thermodynamic properties, established by the specific conditions of each field or formation. Conditioning – a common practice in the liquefied gas industry – is imperative to meet the calculated injection requirements before introduction into the flexible injection pipe, ensuring a successful injection process to the wellhead. This process involves heating and pressurization to transition liquid CO_2 into a supercritical state, which is optimal for subsurface injections. The injection process must ensure that the pressure is high enough to inject CO_2 into the formation, considering the geological and depth-related effects on temperature change.

Hydrate formation can lead to pipeline and valve blockages in CO_2 transportation systems and should therefore be avoided throughout the entire value chain. Effective moisture, temperature and pressure control are crucial to preventing hydrate formation. Maintaining the temperature of CO_2 above the hydrate formation range can minimize the risk of blockage formation throughout the injection system. The temperature of LCO_2 will be raised by a heat exchanger, using either seawater or recovered waste heat from the unit, until the desired temperature is achieved. The LCO_2 can undergo a couple of stages of heat exchange and pressurization as needed until the conditions of the CO_2 injection unit are met; typically, above 0°C, including supercritical conditions. Calculations should also account for heat transfer after departing the unit through flexible riser pipes and their boundary conditions, as well as within the wells beneath the seabed.

INJECTING TECHNOLOGY

CO_2 will be pressurized to the designed injection pressure using a pump. The injection flow rate will be determined based on project objectives and design specifications. Typical reservoir bottomhole conditions require a target pressure range of 100–400 bar in deepwater offshore environments. For extreme high-pressure operations, such as those encountered in ultra-deepwater or high-pressure, high-temperature (HPHT) reservoirs, pressures can reach up to 20,000 pounds per square inch (PSI), or approximately 1,379 bar, requiring specialized equipment and safety measures. Injection rates are monitored using a CO_2 metering device and are directly transported to the subsea wellhead.

A riser is utilized for transferring supercritical CO_2 at appropriate pressure from the FSIU through the Christmas tree to the seabed. The ability of the riser to withstand high pressure and the dynamic movements associated with the FSIU is crucial for the injection process. The wet Christmas tree, installed on the wellhead, serves to control the flow of CO_2 and monitors parameters such as pressure, temperature and flow rates. Surge pressures must be taken into account while assessing the design pressure of the riser and wet Christmas tree. Additionally, the design should consider the unexpected pressure drop due to the sudden closing of the shutdown valve from downstream. This sudden pressure drop may cause CO_2 to transition from the liquid phase to the solid phase, posing risks in the riser.

In CO_2 injection, the pressure in the reservoir typically increases as more CO_2 is injected – unlike oil and gas production where pressure decreases over time. This presents unique safety challenges and requires careful consideration of reservoir temperature variations and their impact on system integrity. These factors must be discussed as key parameters in system design, safety margins and integrity assessments.

FLOATING TECHNOLOGY (MOORING OPTIONS)

In the offshore oil and gas sector, a diverse array of mooring and loading systems have been developed to meet various operational needs. When selecting the mooring system, several critical factors must be considered, including environmental conditions, vessel specifications and operational requirements. A non-exhaustive list of options includes spread mooring, taut-leg mooring, catenary anchor leg mooring (CALM) buoy, internal turret mooring and external turret mooring, with potential for newer concepts to be developed to support emerging technologies.

Spread mooring involves multiple anchors spread out around the vessel, providing stability and flexibility in various sea conditions. Taut-leg mooring uses taut lines connected to anchors, offering enhanced stability by minimizing horizontal movement. CALM buoy employs a buoy to which the vessel is moored, allowing for easier connection and disconnection in calm sea conditions. Internal turret mooring involves a turret integrated within the vessel's hull, allowing the vessel to rotate around the turret while remaining anchored. This provides enhanced stability and operational flexibility in various sea conditions. External turret mooring features a turret located outside the vessel's hull, typically at the bow or stern. It offers similar benefits to internal turret mooring, with the added advantage of easier maintenance and inspection.

Floating storage and injection units (FSIUs) necessitate a permanent mooring arrangement, which includes the integration of high-pressure riser line(s). These risers are securely connected to a subsea transfer line, helping ensure efficient and reliable transfer of CO_2 from the FSIU to the seabed. In addition to the critical factors considered, the selection of the mooring option will be guided by regulatory requirements, classification rules and applicable design standards such as those set forth by the American Petroleum Institute (API).

TECHNICAL RISKS

During early project execution, a detailed risk assessment is to be conducted outlining potential risks, their consequences, and mitigation strategies to enhance safety protocol robustness. Techniques such as hazard identification (HAZID) and failure modes and effects analysis (FMEA) will be used to systematically identify and evaluate these risks. Additionally, change analysis can be employed to assess the impact of modifications in field configurations and operational practices. Given the offshore environment, it is crucial to consider environmental hazards such as severe weather conditions, sea states and potential structural damage due to external factors. The risk assessment should be a dynamic process, with periodic reviews and updates to incorporate new data, insights and regulatory changes, helping ensure that the surrounding safety protocols remain robust and effective throughout the project lifecycle.

The IEA published a CCUS handbook called "CO_2 Storage Resources and their Development" in late 2022 outlining the five technical risks related directly to CO_2, injection and storage operations. These five risks are:

1. Site performance
2. Health, safety and environment (HSE)
3. Containment
4. Induced seismicity
5. Resource interaction

SITE PERFORMANCE RISKS

Assessment and development evaluate reservoir capacity and injectivity to meet project needs. Regular refinements are made to reservoir modeling and site development plans to maintain low performance risks. Optimization focuses on site design, particularly pressure management, involving an integrated analysis of well, near-well and reservoir conditions. Well development plans are periodically reassessed using pumping tests, baseline measurements, modeling and formation pressure data. Brine extraction may be incorporated to enhance injection rate sustainability and relieve reservoir pressure.

HEALTH, SAFETY AND ENVIRONMENT (HSE) RISKS

At elevated concentrations, CO_2 can present risks to human health and the environment. Proper management minimizes the likelihood of toxic CO_2 exposure or asphyxiation. Leakage scenarios are the most hazardous conditions created by sudden or continuous CO_2 releases, such as well blowouts, pipeline leaks or depressurization of storage tanks. The potential impact on the ecosystem includes offshore continuous leakage that might acidify local seawater, impacting vulnerable organisms – though marine ecosystems can tolerate some CO_2 variation. Mitigation measures involve adhering to best practices and regulations during site development and operations. Monitoring programs should track plume behavior, and active safeguards should be implemented to prevent environmental damage from leaks.

CONTAINMENT RISKS

Containment is crucial for helping ensure the long-term safety of CO_2 storage reservoirs. Cap rock integrity plays a vital role in acting as a natural barrier to prevent CO_2 from escaping. Regular monitoring and verification of the storage site are essential to detect any potential leaks and ensure the integrity of the containment system. Implementing risk mitigation measures, such as pressure management and brine extraction, helps maintain the stability of the storage site.

INDUCED SEISMICITY RISKS

Induced seismicity is a potential risk associated with CO_2 injection and storage activities. Seismic risk assessment is necessary to evaluate the likelihood of induced seismic events. Continuous monitoring of seismic activity in the vicinity of the storage site is crucial to detect any induced seismic events. Mitigation strategies, such as adjusting injection rates and pressures, can be employed to minimize the risk of inducing seismic events.

RESOURCE INTERACTION RISKS

Resource interaction involves assessing the potential impact of CO_2 storage on existing underground resources, such as oil and gas reservoirs. Effective resource management requires coordinating CO_2 storage activities with other resource extraction activities to avoid conflicts and ensure the safe and efficient use of underground resources. Ensuring regulatory compliance is essential to protect existing resources and the environment.

DESIGN CONSIDERATIONS

DRY-PURE CO_2 (IMPURITY)

Limiting impurities in CO_2 injection and transportation systems is critical for optimizing efficiency, meeting environmental standards, preserving infrastructure integrity and helping ensure safety. Effective impurity control is crucial for optimizing injection processes, minimizing environmental impacts and preserving the longevity of transportation infrastructure by mitigating corrosion risks. Impurities such as moisture, oxygen, or other gases can compromise operational efficiency, environmental compliance, infrastructure integrity, end-use quality, and safety, underscoring the importance of stringent impurity control measures in CO_2 transportation systems.

Currently, there is no international standard to regulate acceptable impurity levels in CO_2. However, ongoing research and studies, along with accumulated practical data, provide guidance for current projects. Below are sample cases indicating accepted impurity levels based on various emitters in the CO_2 capture industry. The Northern Lights project, for example, has specific requirements for CO_2 quality, including stringent specifications for impurities like methane, nitrogen, nitrogen oxides, mercury, and argon. The ABS CO_2 Impurities and LCO_2 Carrier Design-Practical Considerations publication offers detailed insights and practical examples on managing impurity levels in large-scale CO_2 projects, highlighting industry standards and current practices for maintaining CO_2 quality.

Table 3: Overview of expected typical CO_2 stream composition (4)

CO_2 Source Capture Technology	Coal-fired Power Plant Amine-based Absorbtion	Coal-fired Power Plant Ammonia-based Absorbtion	Coal-fired Power Plant Selexol-based Absorbtion	Coal-fired Power Plant Oxyfuel Combustion	Natural Gas Processing Amine-based Absorbtion	Synthesis Gas Processing Rectisol-based Absorbtion
CO_2	99.8%	99.8%	98.2%	95.3%	95.0%	96.7%
N_2	2,000	2,000	6,000	2.5%	5,000	30
O_2	200	200	1	1.6%		5
Ar	100	100	500	6,000		
NO_x	50	50		100		
SO_x	10	10		100		
CO	10	10	400	50		1,000
H_2S			100		200	9,000
H_2			1.0%			500
CH_4			1,000		4.0%	7,000
C_2+					5,000	1.5%
NH_3	1	100				
Amine	1					

Overview of expected typical CO_2 stream compositions of six CO_2 source and capture technology combinations that are responsible for the most extreme impurity levels. The concentrations are given on a volume basis (ppm where not labeled as %).

WELL CONDITIONS AND PARAMETERS DICTATE SYSTEM DESIGN FACTORS

The CO_2 injection reservoir condition is a pivotal factor in CCS operations due to its direct influence on injection feasibility, efficiency and safety. Reservoir pressure, temperature, and geological properties play crucial roles in determining CO_2 behavior – including density, viscosity, and phase behavior – which is essential for designing injection strategies and predicting CO_2 plume migration within the reservoir. Maintaining CO_2 in a supercritical state is paramount for maximizing storage capacity and minimizing buoyancy effects, necessitating a comprehensive understanding of reservoir conditions. Additionally, reservoir conditions affect geochemical interactions of CO_2 with formation fluids and rock minerals, which impact reservoir integrity, CO_2 trapping mechanisms and long-term storage security. Accurate reservoir condition data requires numerical simulations and predictive modeling to optimize injection design, storage capacity assessment, reservoir performance prediction and risk evaluation. By integrating the reservoir condition parameters into injection design calculations such as injection rates, pressures and well configurations, more tailored approaches can be developed to maximize storage efficiency and minimize operational risks.

SUDDEN PRESSURE DROPS

Sudden pressure drops in CO_2 systems can lead to phase changes, causing LCO_2 to solidify into dry ice. This phenomenon occurs due to the Joule-Thomson (JT) effect and the thermodynamic properties of CO_2. The JT effect describes the temperature change of CO_2 when it expands from high pressure to low pressure at constant enthalpy. The specific temperature, pressure and expansion ratio determine whether CO_2 will solidify. The sudden solidification of CO_2 can block pipelines, valves or injection wells, disrupting the flow and compromising system operations.

Additionally, the mechanical stress, thermal stress and residual stress induced by solid CO_2 formation can damage infrastructure components, posing safety risks and jeopardizing system integrity. Mechanical stress refers to the physical forces exerted by solid CO_2, causing deformation and potential damage. Thermal stress arises from temperature changes during CO_2 solidification, leading to expansion or contraction of materials. Residual stress remains in materials after the initial cause of stress is removed, often due to phase transformations or thermal cycles.

To mitigate these risks, it is crucial to implement real-time monitoring and control systems to maintain stable pressure levels throughout the CO_2 transportation and injection process. In addition, appropriate insulation and heating systems can help maintain consistent temperature levels and prevent solidification. Insulation slows down heat transfer by trapping air, reducing the rate at which CO_2 cools during expansion. Heating systems, such as heat exchangers using seawater or recovered waste heat, can condition LCO_2 to maintain its temperature above the solidification point. Automated pressure relief valves and regulators can also help prevent sudden pressure drops. These measures will help reduce the risks associated with sudden pressure drops in CO_2 systems, ensuring safe and efficient operation.

ADDITIONAL TECHNOLOGIES POTENTIALLY ONBOARD FSIUS

ONBOARD CARBON CAPTURE

Onboard carbon capture technology has the potential to help the maritime industry curb emissions from the sector. This technology can be adapted for FSIU operations to further reduce emissions. These systems utilize various methods such as absorption, adsorption, membrane separation, cryogenic processes and chemical looping to capture CO_2 from exhaust gases or other onboard sources. The captured CO_2 can then be stored and transported in LCO_2 form then conditioned to meet injection requirements for permanent sequestration.

However, onboard carbon capture technology also presents challenges that must be addressed before widespread adoption. These challenges include the additional energy requirements of the capture process, which can be approximately 10 percent of the energy used by the engine (though this figure requires further research and validation); the space needed for onboard installation, which may not be a significant issue for FSIU operations; and the economic viability of implementing such systems.

CURRENT LCO_2 TRANSPORT TRENDS

LCO_2 SHIPPING TECHNOLOGY

In the realm of offshore floating CO_2 injection facilities, the optimal tank shape for cryogenic temperature transfer is typically cylindrical, bi-lobe Type C tanks, per The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). This tank shape provides uniform stress distribution, minimizing the risk of structural failure under extreme conditions. Advanced insulation technology, such as polyurethane foam (PUF) or other suitable insulation based on water depth, temperature, pressure, and other project specifications, is crucial for maintaining the cryogenic temperatures required to keep CO_2 in liquid form to reduce heat ingress and help ensure energy efficiency. The size range of LCO_2 vessels for the current CCS industry model is typically around 7,500–100,000 cubic meters (m3), which is primarily in compliance with the IGC Code with some exceptions as provided by IMO. This size balances the need for substantial storage capacity with the operational flexibility required to navigate various offshore environments and meet the growing demand for CO_2 transportation and injection. ABS has dedicated requirements for LCO_2 carriers.

THE EMERGING MARKET FOR LCO_2 CARRIERS

While pipelines remain the most practical method of CO_2 transportation for the current market, the LCO_2 shipping market offers promising potential for longevity of the CCS industry. Although the initial capex for pipeline development is relatively high, pipelines transport CO_2 in a supercritical or dense phase, reducing the need for extensive liquefaction and heat exchange processes, thus lowering overall operational expenditure (opex). Nevertheless, the emerging CO_2 shipping business model offers greater flexibility and can facilitate the various CO_2 transport networks, presenting additional advantages in certain scenarios. For example, LCO_2 carriers could be utilized in transporting CO_2 to offshore hubs where pipelines are not available. This flexibility in transportation ensures that CO_2 can be efficiently delivered to storage sites, regardless of pipeline infrastructure limitations.

Middle-sized CO_2 transportation vessels are under construction for the Northern Lights project, which delivers a message that a value-added supply chain is possible via shipping. Studies suggest that the cost-effective range for shipping is at least around 1,000–1,500 kilometers longer than a pipeline, despite CO_2 shipping entailing higher opex.

CONCLUSION

The deployment of CCS technologies, especially in offshore environments, could be a pivotal advancement toward achieving emissions reduction goals. Integrating FSIUs alongside advanced CO_2 transportation methods, such as LCO_2 carriers, presents an innovative solution to the challenges of offshore CO_2 storage. Technological advancements in LCO_2 offloading, storage tank technology and conditioning processes are crucial for efficient and safe CO_2 injection and permanent storage.

Moreover, the evolving regulatory landscape and CCS network business models are instrumental in driving the adoption and scalability of CCS projects. Comprehensive risk assessments encompassing technical, health, safety and environmental (HSE) risks are vital to promoting the long-term safety and effectiveness of CO_2 storage. International cooperation and standardization are essential for harmonizing regulations and fostering innovation in CCS technologies.

By addressing these critical aspects, the CCS industry could have significant potential for supporting reduced emissions and promoting sustainable energy practices. The future of CCS lies in continued research, development, collaboration, and use of cutting-edge technologies to overcome existing limitations and maximize the potential of offshore CO_2 storage solutions.

REFERENCES

PUBLICATIONS

1. The International Energy Agency (IEA). Operating and planned CO_2 storage facilities by storage type as of 2023. The International Energy Agency (IEA). [Online] 2023. https://www.iea.org/data-and-statistics/charts/operating-and-planned-co2-storage-facilities-by-storage-type-as-of-2023.
2. Review of CO_2 sequestration mechanism in saline aquifers. Luo, Ang, et al. 4, 2022, Natural Gas Industry B, Vol. 9, pp. 383-393.
3. Center for International Environmental Law (CIEL). Deep Trouble: The Risks of Offshore Carbon Capture and Storage. [Online] 2024. https://www.ciel.org/wp-content/uploads/2023/11/Deep-Trouble-The-Risks-of-Offshore-Carbon-Capture-and-Storage.pdf.
4. SINTEF. CO_2 impurities: What else is there in CO_2 except CO. [Online] blog.sintef.com/sintefenergy/energy-efficiency/what-else-is-there-in-co2-except-co2/.
5. The CCUS Hub. A Playbook for regulators, industrial emitters and hub developers. [Online] June 2023. https://ccushub.ogci.com/wp-content/uploads/2023/06/CCUS-Playbook_EN_2023.pdf.
6. The International Energy Agency (IEA). Net Zero Emissions by 2050 Scenario (NZE). The International Energy Agency (IEA). [Online] https://www.iea.org/reports/global-energy-and-climate-model/net-zero-emissions-by-2050-scenario-nze.
7. Global CCS Institute. Global Status of CCS 2023 - Report & Executive Summary. [Online] November 2023. https://www.globalccsinstitute.com/resources/publications-reports-research/global-status-of-ccs-2023-executive-summary/.
8. Club CO_2. [Online] https://www.club-co2.fr/en.
9. IEA. CO_2 Storage Resources and their Development: An IEA CCUS Handbook. [Online] Nov 2022. https://iea.blob.core.windows.net/assets/42d294af-ce07-44c7-9c96-166f855088e8/CO2storageresourcesandtheirdevelopment-AnIEACCUSHandbook.pdf.
10. —. CO_2 Transport and Storage. The International Energy Agency (IEA). [Online] 2024. https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage.
11. The International Energy Agency (IEA). Shipping and offshore pipeline transportation costs of CO_2 by distance. The International Energy Agency (IEA). [Online] 2020. https://www.iea.org/data-and-statistics/charts/shipping-and-offshore-pipeline-transportation-costs-of-co2-by-distance.
12. Zero Emissions Platform (ZEP). The cost of CO_2 transport. [Online] https://zeroemissionsplatform.eu/document/the-costs-of-co2-transport/.
13. Numerical modelling of long-term CO_2 storage mechanisms in saline aquifers using the Sleipner benchmark dataset. Akai, Takashi, et al. 110, 2021, International Journal of Greenhouse Gas Control.
14. A review of large-scale CO_2 shipping and marine emissions management for carbon capture, utilisation and storage. Al Baroudi, Hisham, et al. 287, 2021, Applied Energy.
15. Enabling Large-Scale Carbon Capture, Utilisation, and Storage (CCUS) Using Offshore Carbon Dioxide (CO_2) Infrastructure Developments—A Review. Batum, Melissa, et al. 10, 2019, Energies, Vol. 12.
16. Brownsort, Peter. Offshore offloading of CO_2: Review of single point mooring types and suitibility. Edingburgh Research Archive. [Online] May 2015. https://era.ed.ac.uk/handle/1842/15712.
17. —. Ship transport of CO_2 for Enhanced Oil Recovery - Literature Survey. Edinburgh Research Archive. [Online] January 2015. https://era.ed.ac.uk/handle/1842/15703.
18. de Kler, Robert, et al. Transportation and unloading of CO_2 by ship - a comparative assessment. s.l. : CATO, 2016.
19. Numerical Analysis of Flow Characteristics in an Injection Tubing during Supercritical CO_2 Injection: Application of Demonstration-scale CO_2 Storage Project in the Pohang Basin, Korea. Jung, Woodong, et al. 4, August 2022, Journal of the Korean Institute of Gas, Vol. 26, pp. 9-17.
20. Numerical Analysis of CO_2 Behavior in the Subsea Pipeline, Topside and Wellbore With Reservoir Pressure Increase over the Injection Period. Min, Il Hong, et al. 4, November 2016, Journal of the Korean Society for MArine Environment & Energy, Vol. 19, pp. 286-296.
21. Design and Construction Study of an Injection Facility for CO_2 Offshore Storage. Moon, Hung-Man, et al. 2, June 2018, The Journal of Engineering Geology, Vol. 28, pp. 207-215.

22. Conceptualization of CO_2 Terminal for Offshore CCS Using System Engineering Process. Noh, Hyonjeong, et al. 22, November 2019, Energies, Vol. 12.
23. Ceto: Technology Qualification of Low-Pressure CO_2 Ship Transport. Notaro, Gabriele, et al. 2022. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16).
24. Ship-based Offshore CCS Featuring CO_2 Shuttle Ships Equipped with Injection Facilities. Ozaki, Masahiko, Ohsumi, Takashi and Kajiyama, Ryuichiro. 2013, Energy Procedia, Vol. 37, pp. 3184-3190.
25. At what Pressure Shall CO_2 Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping. Roussanaly, Simon, et al. 18, September 2021, Energies, Vol. 14.
26. Topside process design for the liquid CO_2 Injection. Zahid, Umer, Kim, Yong Heon and Ahmed, Usama. 2017, Computer Aided Chemical Engineering, Vol. 40.
27. Reyes-Lúa, Adriana, et al. CO_2 ship transport: Benefits for early movers and aspects to consider. CCUS Projects Network. 2021. 4th Report of the Thematic Working Group on: CO_2 Transport, Storage, and Networks.
28. Kenneth René Simonsen, Dennis Severin Hansen, Simon Pedersen., 2023. Challenges in CO_2 transportation: Trends and perspectives.

ABS PUBLICATIONS

ABS *Guide for Classification and Certification of Subsea Production Systems Equipment and Components*, August 2017

ABS *Guidance Notes on Risk Assessment Applications for the Marine and Offshore Industries*, May 2020

ABS *Carbon Capture, Utilization and Storage*, August 2021.

ABS *Setting the Course to Low Carbon Shipping – Zero Carbon Outlook*, June 2022.

ABS *Requirements for Onboard Carbon Capture and Storage*, December 2022

ABS *Rules for Building and Classing Marine Vessels*, January 2023.

ABS *Rules for Alternative Arrangements, Novel Concepts and New Technologies Part 1D*, January 2024

ABS *Requirements for Liquefied Carbon Dioxide Carriers*, January 2024.

ABS *Rules for Building and Classing Offshore Units*, January 2025

ABS *CO_2 Impurities and LCO_2 Carrier Design: Practical Considerations*, 2025.

LIST OF ACRONYMS AND ABBREVIATIONS

BOG	Boil-off Gas
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilization and Storage
CIEL	Center of International Environmental Law
CO_2	Carbon Dioxide
CAPEX	Capital expenditure
EOR	Enhanced Oil Recovery
FPSO	Floating Production, Storage, and Offloading
FLNG	Floating Liquefied Natural Gas
FSU	Floating Storage Unit
FSIU	Floating Storage and Injection Units
HSE	Health, Safety and Environment
IEA	The International Energy Agency
IGC Code	The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IPCC	The Intergovernmental Panel on Climate Change
LCO_2	Liquid Carbon Dioxide
Mt	Megatonne (106 tonnes, million tonnes)
NZE	Net Zero Emissions by 2050 Scenario
OPEX	Operational Expenditure
PUF	Polyurethane Foam
UNFCCC	United Nations Framework Convention on Climate Change

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